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Rapid Manufacturing of Functional Engineering Components

Rhys Owen Jones, Pejman Iravani, Adrian Bowyer

2012

Abstract

This report details the work undertaken with the end goal of creating a machine capable of additive manufacturing of functional components using various materials. The research focuses on the manufacture of functional electro-mechanical components.

This report includes a literature review additive manufacturing technologies and a summary of the research undertaken thus far. The work focused on enabling the RepRap machine to utilise multiple materials using the Robocasting and Fused Filament Fabrication processes. This resulted in the manufacture of several multiple material components.

Note: This report is a summary of the MPhil to PhD transfer report submitted by Rhys Owen Jones in October 2010.

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List of Abbreviations

3DP Three Dimensional Printing

ABS Acrylonitrile Butadiene Styrene

AM Additive Manufacturing

CAD Computer Aided Design

EBM Electron Beam Melting

FDM Fused Deposition Modelling, a commercial trademark of Statasys Inc detailing the FFF process

FFF Fused Filament Fabrication

J-P Jetted Photopolymer

LOM Laminated Object Manufacture

MM Single Jet Inkjet

PDMS Polydimethylsiloxane

PEEK Polyether ether ketone

PLA PolyLactic Acid

PTFE Polytetrafluoroethylene

RepRap Replicating Rapid Prototyper

RP Rapid Prototyping

RPEC Rapid Prototyping of Electronic Components

RTV Room Temperature Vulcanising

SLA Stereolithography

SFF Solid Free-form Fabrication

SLS Selective Laser Sintering

STL A file format defining a triangulated surface of a three dimensional object

Chapter 1

Introduction

1.1 Aims and Goals of the Research

This research aims to test the following:

> Solid Freeform Fabrication processes are sufficiently versatile to manufacture complex electro-mechanical devices, such as electric motors and valves, and thereby enable the creation of functional components

The goals for the research are:

1. Enable the utilisation of functional materials by RepRap 3D printers using Robocasting in parallel with the fused filament fabrication process previously developed.

2. Reduce the requirements on material rheology in the Robocasting process through the use of mechanical constraint between neighbouring materials rather than relying on chemical adhesion

3. The design and manufacture of complex electro-mechanical devices utilising Solid Free-form Fabrication technology.

In short, this research aims to improve additive manufacturing technology by enabling the manufacture of more functional components in a low-cost manner.

Chapter 2

Literature Review

2.1 Additive Manufacturing

The field of Additive Manufacturing (AM) is the class of technologies that enable components to be manufactured, as the name implies, on an additive basis (typically layer by layer). The roots of Additive Manufacturing began in the 19th century, and AM in its current form is the result of many technologies being developed in parallel. Therefore, the resultant methods that are utilised today each have their own strengths, weaknesses and applications. This section will explore the ongoing development of additive manufacturing, including the transition to open source technologies, whilst highlighting relevant research in the sector within the context of manufacturing functional components that a self-manufacturing machine inevitably requires.

It should be noted, that this section will frequently cite work undertaken by the open source RepRap, Fab@Home and other communities. These developments have been achieved outside the traditional sources of research and development, often by enthusiasts with no external assistance or funding, and therefore do not come with the scientific scrutiny to which academic and (to a lesser extent) commercial activities are subjected.

However, it is the author's opinion that this only makes the achievements detailed more substantial because they demonstrate that the methods developed are sufficiently robust that they can be established with limited resources. Furthermore, due to the open source nature and the popularity of these projects, results and experiments are frequently repeated and verified by different operators, in different continents with different machines. Again in the author's opinion, this is a substantially more robust and reliable measure of validity than peer review. Nevertheless, where this is the case, achievements without academic review shall be highlighted here and taken with caution.

2.1.1 Definitions

As will be detailed throughout the following chapter, the field of additive manufacturing is a sector that can trace its routes back to the 19th century. With the modern advances of CAD technology, AM's implementation in the design cycle, and AM being a potential manufacturing technique, revenues generated by the products and services of companies within the additive manufacturing industry are growing at the astounding rate 26.4% per annum and stand at approximately \$1.1 billion as of 2010 [1]. Unsurprisingly, this has lead to substantial developments in recent times, which coupled with disjointed development, has led to some ambiguity in the terms used in field. For clarity, the author presents the following interpretations that will be used within this report. These definitions have been derived from Gibson et al. [2] and Chua et al. [3]

Rapid Prototyping (RP)

A term used across many industries to describe a mechanism for quickly producing a *representation* of a system or part before the final manufacturing process is established. Equally, this term is applicable to software development, where the term can be used in developing software in a piecewise fashion to allow clients to provide feedback during development. Arguably, this is a flawed definition. It does not reflect the improvements in output quality that have been occurring in recent times. This has lead such technologies to become a more integral part of the manufacturing process; in some cases parts are manufactured by such techniques for inclusion in the final product.

Furthermore, the term rapid is a misdemeanour, particularly when for some systems and designs models can take several days to produce. A working group has recently been formed within American Society for Testing and Materials (ASTM) International to conceive a more appropriate term. At the time of writing, new terminology has not been defined; however recent ASTM standards refer to the term Additive Manufacturing. [2]

Additive Manufacturing (AM)

Additive Manufacturing refers to the collection techniques of fabricating models typically generated using a Computer Aided Design (CAD) package, in an additive fashion without the need for any process planning. The model is typically sliced into a series of two-dimensional layers, before being manufactured layer by layer.

Solid FreeForm Fabrication (SFF)

An alternative to the term additive manufacturing. The reference to the term FreeForm refers to ability of many AM systems to provide "complexity for free", where for example a simple solid cube would have the same build time as a part with the same total volume but containing a complex mesostructure.

3D Printing(3DP)

The term 3D Printing refers to a subset of solid free-form fabrication and AM technologies which encompass the cheapest technologies.

Somewhat confusingly, 3D printing is also an alternative for solvent jet printing (see section 2.1.3), within the context of this report 3D printing will only refer to low cost solid free-form fabrication/AM systems.

2.1.2 Foundations of Additive Manufacturing

Whilst the concept of manufacturing objects in layers dates to the building of the pyramids, if not before, the underpinnings of modern rapid prototyping technologies may be traced back to the advent of photosculpture & topology. Much of the background presented here is based on Beaman's summary[4].

Photosculpture

During the 19th century, attempts arose to create physical replicas of three-dimensional objects. One such attempt was undertaken by François Willème, whereby an object was placed at the centre of circular chamber and simultaneously photographed by 24 different cameras equidistantly spaced around the circumference. Silhouettes of these photographs would then be used by craftsmen to assist in the manufacture of three-dimensional models. In 1904, Baese developed a refinement on this technology, by employing the use of photosensitive gelatine, which when exposed to a graduated light source, expanded proportionally to the exposure time when treated with water[5].

Perhaps the earliest technique with direct parallels to a modern rapid prototyping technology, namely stereolithography, was developed by Munz in 1951[6]. His system was centred on a transparent photo-emulsion that hardened when exposed to a photographic negative. This photoemulsion was contained within a large vat built on a piston. After each layer was exposed, the piston descended allowing the next layer to be built on top of the previous layers. The result was that a 3D image of the object was steadily buildt in solid; this could be carved or chemically etched to create a 3D replica of the original.

Topography

In 1892, Blanther developed and patented a novel method of manufacturing contour relief-maps[7]. The process consisted of impressing a contour line from a map onto a wax plate. Following this, Blanther proceeded to cut along this line, leaving a wax

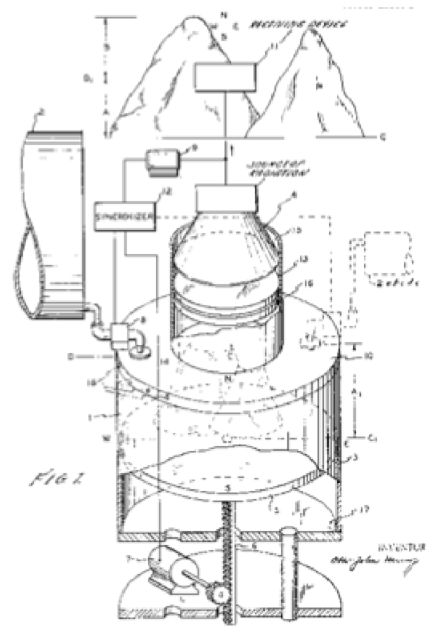


Figure 2.1: Photo-Glyph Recording Schematic[6]

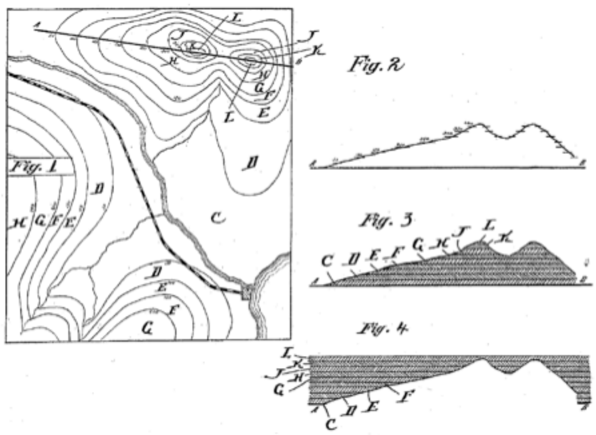


Figure 2.2: Blanther's Contour Relief Map[7]

plate indicating a topographical area above a given altitude. This process was repeated for the remaining contour lines from the map, before stacking and smoothing these wax plates. The process resulted in a three dimensional surface corresponding to the altitude indicated by the original contour lines. After creating a negative form of this surface, a regular map was then be pressed between these surfaces to create a three-dimensional contour relief map.

Whilst the methods of Blanther were furthered in the early 20th century by Perera, Zang & Gaskin, the fundamentals of the process were not substantially developed until the work of Matsubara in 1972[4]. He proposed a topographical process based on photohardening resins, which involved coating powders such as graphite. These coated powders would be spread into a layer and heated to form a sheet of uniform thickness. Desired sections of this sheet would then be selectively hardened using a light source, before the unhardened sections of the sheet were dissolved by a suitable solvent, leaving one layer of the required geometry. This process could then be repeated to form multiple layers, which could be stacked together to form a three dimensional mold.

The Birth of Modern Additive Manufacturing

There are other labour intensive methods besides those outlined in the preceding section which have similarities with modern AM. The first published account of a modern additive manufacturing process occurred in 1981. Kodama investigated three alternative processes to fabricate a 3D model[8]. The fundamental approach of all three methods was to utilise a commercial photo-hardening liquid. Upon UV illumination, unsaturated polyester within the liquid turned to a cross-linked polymer and solidified. The difference between each method lies in the approach used to accurately control the UV illumination:

1. A mask was implemented to control the exposure of the UV source. After the exposure of one layer, the model was then lowered into a liquid photopolymer vat in order to create the next layer

2. Implementing a mask-based approached as in 1), but locating the UV source and the mask at the bottom of the vat, and raising the model in order to create each layer.

3. Utilising an X-Y plotter, an optical fibre and lens to solidify a small segment of one layer accurately. The plotter scanned the cross section of the model to solidify an entire layer fully. After the exposure of an entire layer the model would be lowered into a liquid vat to enable the production of the following layer.

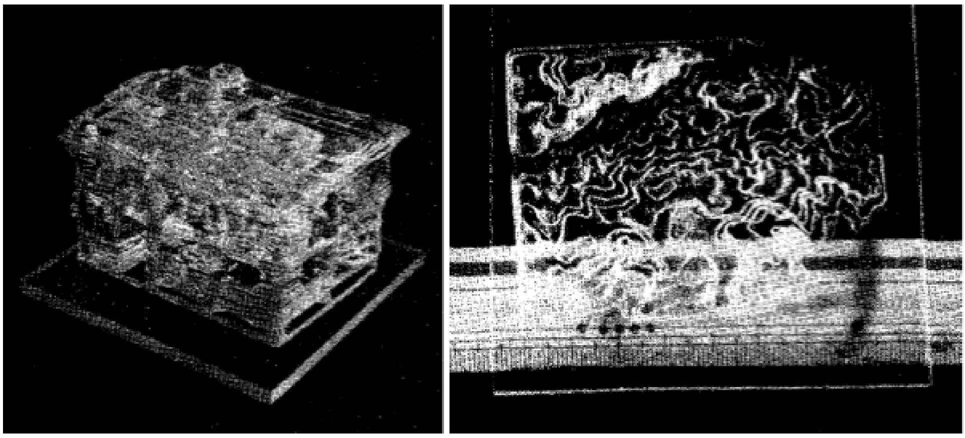
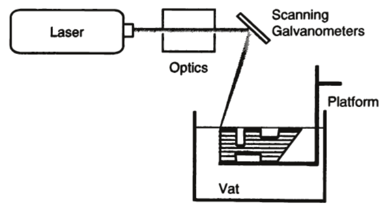


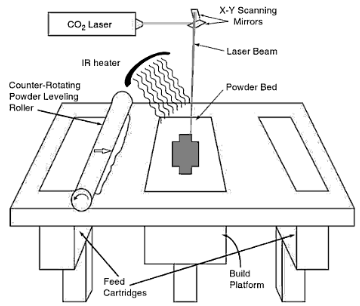
Figure 2.3: Examples of Models Produced Using Kodama's Techniques [8]

2.1.3 Modern Additive Manufacturing

Additive methods are more versatile than subtractive manufacturing technologies (they can make more complicated shapes), and the complexity of part design does not impinge on its cost. Further, AM systems are capable of manufacturing components that would be near impossible to make using traditional systems. However, within Additive Manufacturing several different technologies exist, each with their own set of characteristics, capabilities and limitations. The following table describes the established commercially available AM methodologies:

Table 2.1: Descriptions of the Established Solid Free-Form Fabrication Technologies. Unless otherwise stated, illustrations of courtesy of Gibson et al.[2]

Method	Description	
Stereolithography (SLA)	The process is built around a vat of liquid photopolymer, a laser beam and the appropriate optics, and a movable platform. At the start of the process, the platform is such that its surface is just below the surface of the photopolymer. The optics focus the laser onto the liquid surface, and proceed to scan a two dimensional cross section of the desired part causing the photopolymer to solidify. The entire platform drops to cover this section with more liquid. This process is then repeated until the complete part is manufactured.	

Selective Laser Sintering (SLS)	A large quantity of powdered material is stored in a feed cartridge. A piston in the cartridge enable the upper surface height of the powder to be accurately adjusted. A roller is then capable of spreading powder from the feed cartridge onto the build platform. A laser beam, typically CO_2, traces over the powder, increasing its temperature above the material's melting point enabling it to fuse together. A second piston controlling the height of the build platform is then lowered, to allow a further layer of powder to be deposited onto the build platform using the mechanism previously described. Unlike many other SFF technologies, the unfused powder in lower layers is able to support the part geometry in upper layers from deforming. Thus additional support material is not required for complex geometries.	

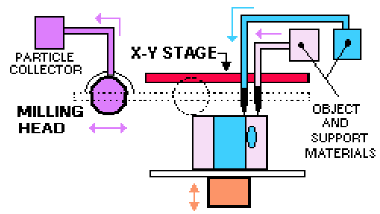
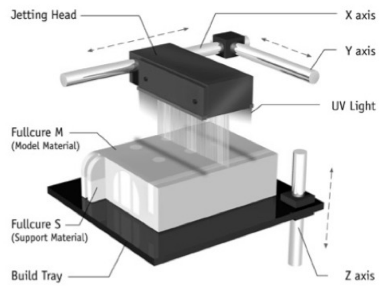
<table>
<tr><td>Single Jet Inkjet (MM)</td><td>Two single jets separately contain a plastic build material, and a wax support material, stored in heated reservoirs. Both jets move in X/Y directions whilst depositing droplets of each material at the appropriate positions. After deposition, the droplets rapidly drop in temperature causing them to solidify. Subsequently, a milling head removes a small amount of material from the top of the layer to ensure uniform thickness, whilst any swarf is collected by vaccum. The entire build platform then drops a small amount to allow the manufacture of another layer using the same process. Illustration courtesy of the Worldwide guide to Rapid Prototyping.[9]</td><td>
</td></tr>
<tr><td>Jetted Photopolymer (J-P)</td><td>The Jetted Photopolymer process is very much a hybrid of traditional 2D inkjet printing and Stereolithography. An array of inkjet jetting heads is used to deposit a small layer of photocuring material. Subsequently, the material is cured using UV light. This entire process occurs on a movable build tray that is lowered to enable the next layer to be manufactured. Typically, other photocuring materials or waxes are required for a support material.

Illustration courtesy of Objet Geometries Ltd. [10].</td><td>
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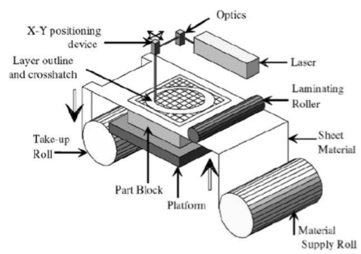
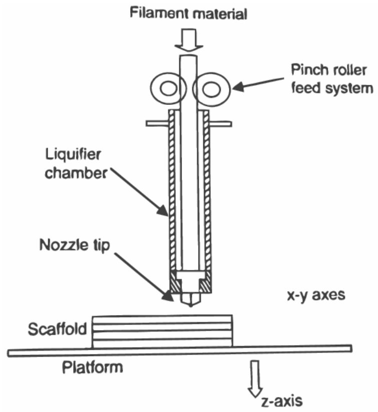
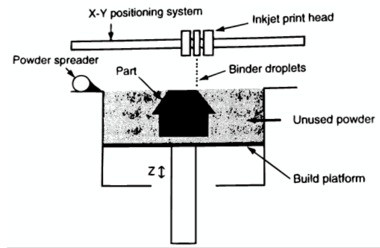
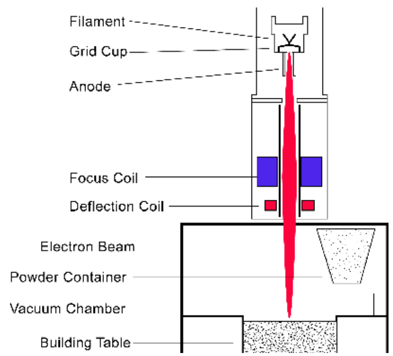
Laminated Object Manufacturing (LOM)	Material, typically paper, is supplied in sheet form on a roll. This material is fed over a platform and secured to a take up roll. A cross section of the part is then cut using a CO_2 laser and then laminated. The platform is lowered, and fresh material is rolled over the build. This process continues to build subsequent layers. No support material is required as any excess material within the voids of the part is crosshatched and can act as a support structure.	
Fused Filament Fabrication (FFF). Also known as Fused Deposition Modelling (FDM)	Material, typically thermoplastic, supplied in filament form, is fed into liquifier chamber where it is heated to a semi-liquid state and deposited through a nozzle onto a build platform. Upon leaving the nozzle, the material quickly solidifies. In a continuous process, the extruder is traversed in the X & Y axis relative to the bed to create a layer of the part. Typically, a second extruder capable of depositing support material is also used in the process. This support, may either be designed such that it is easy to breakaway in post processing, or alternatively may be soluble in a suitable solvent.	

Solvent Jet Printing(frequently referred to as Three-Dimensional (3D) Printing)	A powder spreader deposits an even layer of powder onto a build platform that is capable of movement in the Z axis. The machine then uses an Inkjet print head to deposit binder solution onto the loose powder to glue the powder together, to form a layer of the final part. Finally, the build piston is allowed, and the process repeated for the subsequent layers. Any unused powder is capable of supporting any layers above, thus no support material is required.	
Electron Beam Melting (EBM)	The process is centred around an electron beam gun, whereby a tungsten filament is heated until the point that it become incandescent. At this point, the filament produces a cloud of charged electrons. A annode, also contained within the gun, induces the electrons to travel through the gun at extremely high speed, approximately half the speed of light, towards the annode. Two sets of magnetic coils, one for focusing, one for position control, control this stream of electrons towards a desired point in a bed of powder. Upon hitting the powder, the electrons kinetic energy is converted to thermal energy, melting the powder fusing it together. This beam is then traced over the powder to form one layer of part, before more powder is added and process repeated to build subsequent layers. Image Courtesy of Hiemenz [11].	

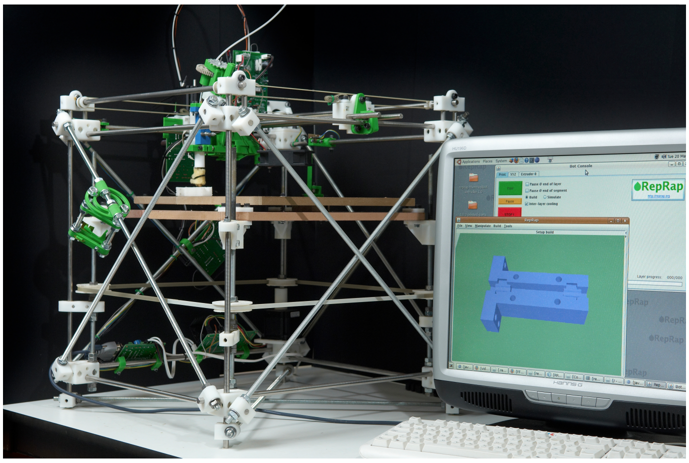


Figure 2.4: RepRap V1.0 - Darwin. The device is capable of self-manufacturing all parts shown in either white or green(except the thermal insulator on the extruder)

2.1.4 The RepRap Project

Materials & Extrusion Mechanisms

Initially, the RepRap team utilised Polycaprolactone (PCL) polymer owing to its low melting point, thereby lowering power consumption required for the extruder design. Crucially however, its low coefficient of friction ensured that the polymer transport mechanism within the extruder needed to provide substantial amounts of grip. Thus, the resulting extruder design required multiple pinch wheels and therefore became unnecessarily complex[12].

Figure 2.5 shows the latest iteration of the RepRap extruder design. The device has a gear ratio of 5:1(utilising gears that RepRap is capable of producing for itself), in order to allow for increased control over the plastic filament feed. In this case, a single pinch wheel is employed, with a splined insert attached the driven gear compressing the plastic filament against an idler bearing. In addition, the position this idler bearing is controlled by adjusting a series of compression springs at the front of the device. The compression springs ensure that the force acting on the filament remains approximately constant regardless of any small variations in filament diameter. The filament is fed into a thermal barrier (the white cylinder), in this case PTFE due to its low friction coefficient[1], in order to prevent the heat from the nozzle spreading to the rest of the

[1]PEEK has been previously trialed for its improved mechanical robustness compared to PTFE, but

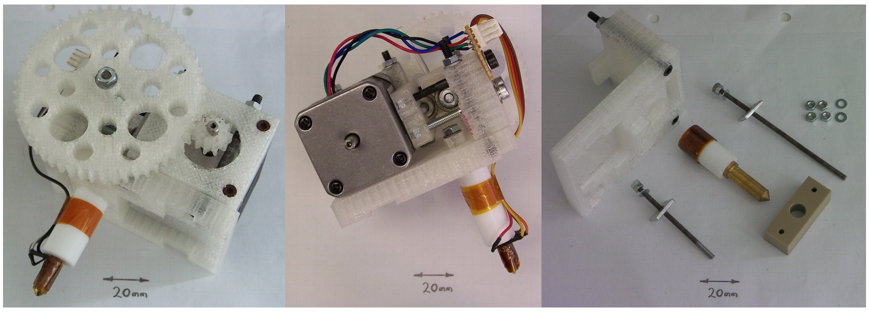


Figure 2.5: The geared extruder design, showing front (left) and back (middle) views. In addition, a further modification implementing a PEEK bracket & a nozzle the encases the thermal barrier to reduce PTFE insulator swell is shown partially assembled (right)

machine.

Following the thermal barrier, a brass nozzle with an orifice of 0.5mm is used to both heat and extruder the thermoplastic filament. This orifice diameter was chosen as it was deemed a good compromise between acceptable accuracy and reasonable build times.

Given the increased operating temperature of which the more recent extruder designs were capable, other materials could potentially be used. Given the low friction coefficient of PCL, and the "stringy" nature of the extrudate, PCL was only capable of producing poor quality parts. Therefore, a transition was made to utilise Acrylonitrile Butadiene styrene (ABS)[2].

Whilst ABS solved many of the problems initially hindering the results of the RepRap project, one fundamental issue remained - part warping. Owing to the inherent process of fused filament fabrication, the plastic filament needs to be heated to its melting point before solidifying when cooling. However, this change in temperature enables thermal contraction, and thus the bottoms of parts have the tendency to curl away from the build base, although this issue is reduced for small parts. Proprietary machines typically solve this issue by running the entire process within a heated chamber. However, it was deemed by the RepRap core team that incorporating a heated chamber into the design would increase the complexity of the design, and thus harm its ability to replicate.

proved unreliable

[2]A material that is also used in many proprietary FDM 3D printers

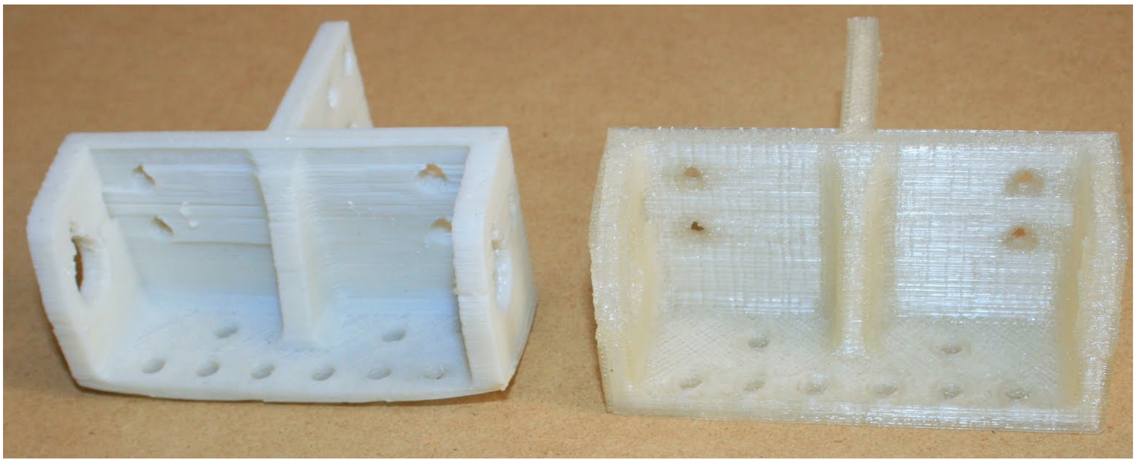


Figure 2.6: A comparison of the build quality, between ABS (left) and PLA (right) circa September 2009. Note the warping on the ABS part. [13]

In parallel, the use of Polylactic Acid (PLA) as a build material was being investigated by team-member Vik Olliver. PLA is a biologically sourced thermoplastic, which is biodegradable and more eco-friendly than oil-based polymers. It was discovered during this research, that PLA suffers substantially less from contraction on cooling and is described by Bowyer as "the almost perfect" material for the fused filament fabrication process. However it tends to "string", leaving extrudate sticking out from the part surface due to in-air movements required during the build process. Whilst this can be reduced by reversing the extruder before in-air movements, some stringing still remains.

Subsequently to this, a heated bed has been developed by the RepRap community. Whereby an aluminium build base is heated by nichrome heater wire. This produces similar effects to that of the heated build chamber used in commercial systems, but in a simple, low-cost manner.

RepRap II - Mendel

A second-generation RepRap design, "Mendel", was released on October 13th 2009. The Mendel design focuses on reducing the amount of Cartesian frame to the design, and thus reduce the amount vitamin components required. In addition, Mendel incorporates rolling element bearings for constraint, resulting in a more robust and portable

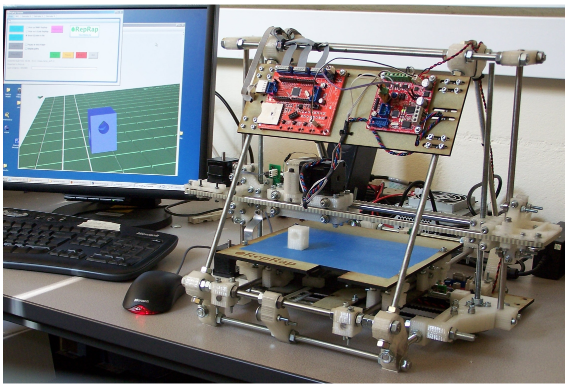


Figure 2.7: RepRap II: Mendel [12]

machine. However, at the inception of the work undertaken in this report, Mendel was only capable of utilising a single material during any build.

2.1.5 Multiple Material Additive Manufacturing & Functional Components

The use of multiple materials with additive manufacturing has been proposed almost since the technology's inception. In some cases, the use of multiple materials is a fundamental element of how some AM process work e.g. A secondary support material is a key element in the fused filament fabrication process to enable more complex overhanging geometries to be created.

In general, there are three potential techniques by which multiple materials may be implemented, although there are exceptions to this as will be shown later in this section[2]:

- Two or more discrete materials may be deposited next to each other. Typically, systems of this type rely on adhesion between materials, although they may be bonded in some other fashion

- An object can be created such that the part is inherently porous. Subsequently, this part may then be infiltrated by a second liquid material such as an adhesive. This technique is frequently using in the Solvent Jet process to strengthen components.

- The AM process may utilise a feed material that itself is a blend of two or more constituent materials. Some systems also offer the ability to vary the ratio of these materials continuously to give functionally graded components. This technique has been previously demonstrated using EBM or SLS to manufacture nickel-titanium graded components amongst others. [14]

Many reasons are often cited as the driver for reasons for the AM industry to implement multiple materials, these include[2]:

- Improving mechanical properties - Additional materials can allow the bulk mechanical properties of produced parts to be finely controlled, for example tensile strength.
- Increased functionality - Multiple materials may enable parts containing different colours, electrical conductivity, stiffness or other properties. Further, these properties can vary either uniformly or discreetly throughout the component by placing the right combinations of materials in strategic locations
- Improving the AM processes - Additional materials may assist with fabrication, e.g. support material

This section aims to summarise research undertaken into the implementation of functional materials and multimaterial techniques in the low cost 3D printing sector. Whilst other multimaterial examples exist, such as the laser-based techniques mentioned previously, they have been excluded from this section due to the large resources such methods require.

Robocasting

In 1999, Joe Cesarano of the Sandia National Laboratory developed a new method of fabricating ceramics entitled Robocasting. Robocasting (often known as Paste Extrusion Freeforming EFF) relies on a syringe to deposit a mixture of ceramic powder,

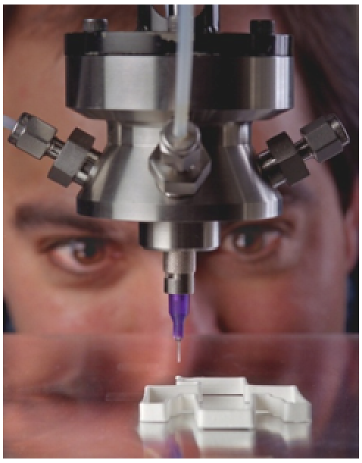


Figure 2.8: Robocasting [15]

water and chemical modifiers. The desired component is then built in an additive fashion; much like fused filament fabrication, using a CNC-controlled positioning head and a pneumatically powered syringe. Typically a liquid-to-solid transition is then realised by solvent evaporation, UV curing or other methods[15]. After parts are formed using Robocasting, they must be dried and then sintered before they are ready for use

Cesarano specifies that Robocasting slurry must meet three key criteria :

1. The slurry must be sufficiently pseudo-plastic to flow through a small orifice at modest shear rates

2. It must be set-up into a nonflowable mass upon dispensing

3. The extrudate must be sufficiently robust to be able to withstand the weight of the above layers without defects

Control of the build time proved to be critical. The build speed needed to closely match the speed at which respective layers transitioned from pseudo-plastic to dilatant. To assist with this transition, parts are typically built on a heated plate from at a temperature of 30 to 60 °C. In the event that the drying rate was too slow, weight from the above neighbouring layers may lead to the yield stress being surpassed resulting in deformed layers with “slumping and non-uniform walls”. Equally, if drying it too fast issues arise with delaminating, warping and cracking.

Cesarano concludes that for effective Robocasting five key parameters require precise control:

1. Viscosity and Rheology of the slurry,
2. Drying kinetics of the extrudate,
3. Computer code for optimal machine instructions,
4. Percent solids in the ceramic powder slurry, and
5. The dispensing rate.

Similar conclusions to Cesarano's above have also been made by Lu et al[16]. A study was conducted on a polymer-based paste before the addition of alumina, LMT, quartz and graphite powders, in order to determine the effect on various parameters. Unsurprisingly, the results show that both powder type and the solvent volume fraction has a substantial effect on viscosity, and subsequently the required extrusion pressure (Figure 2.9).

At higher solvent volumes, viscosity remained reasonably stable with increasing shear rate, and thus was approximately Newtonian. However, with lower solvent fractions, all pastes showed shear-thinning properties (decreased viscosity with increasing shear rate) demonstrating pseudo-plasticity. Furthermore, all pastes were shown to have a critical value of ceramic volume fraction at which a substantial change in the paste viscosity occurs. Thus, an ideal paste should operate around this volume fraction during the deposition process, enabling a "low" viscosity paste to be easily extruded, before a loss of solvent and the associated substantial rise in viscosity and state change; enabling the layer to be sufficiently rigid to hold subsequently deposited layers.

This work culminated in the creation of a variety of structures to show the strengths of the process. Of particular interest, is an electromagnetic bandgap structure, whereby the ability of an object to transmit electromagnetic waves may be controlled by precisely adjusting the separation between infill segments (commonly referred to as roads).

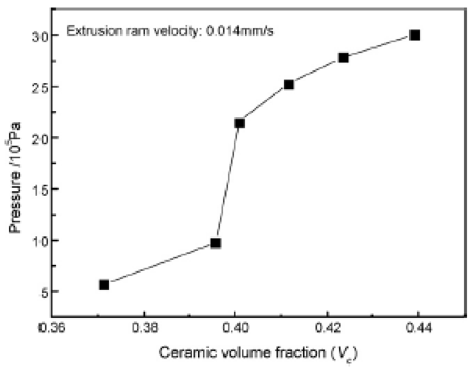


Figure 2.9: Required extrusion pressure for constant volume flow rate for alumina paste with different solvent fractions[16]. Note the step change at 40% volume fraction

Subsequently to these developments, the process has been further refined to function with up to four materials. The multimaterial head consists of four independent material feeds in combination with a miniature mixing chamber and a rotatable paddle. An example of a graded two material component produced on a dual feed mixing head showing a gradual 100% transition from one component material to the other is shown in Figure 2.10.

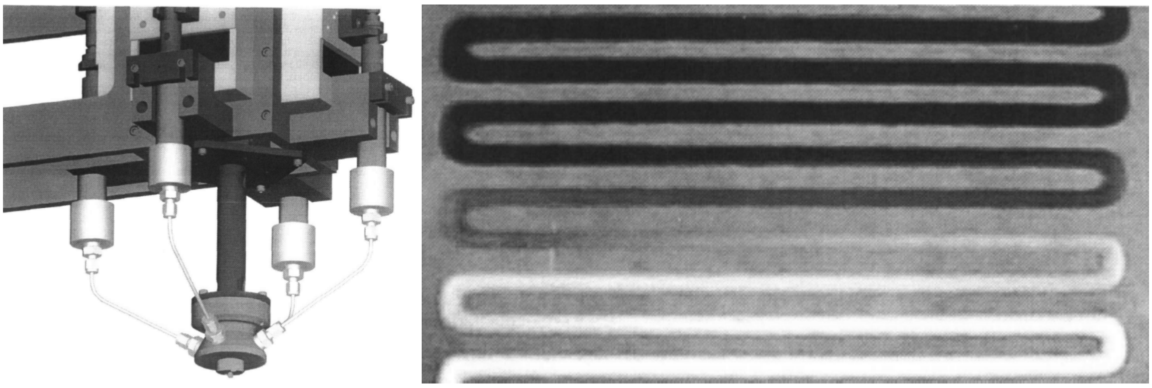


Figure 2.10: Robocasting Multimaterial Head (left) and a graded transition between two ceramic slurries (right)

Further, unlike fused filament fabrication using thermoplastics, Robocasting is only capable of producing extremely basic structures without the use of support material. Whilst support is used for fused filament fabrication, many complex shapes such as overhangs of up to 45° are possible without them. Therefore Cesarano's multimaterial head has been further employed to enable the deposition of a fugitive support material, which may later decompose during the sintering process.

A summary of the materials that have been employed for Robocasting is shown in Table 2.2.

Table 2.2: Current materials employed by Robocasting[15]

Alumina (dense and porous)	PZT
Al_2O_3/TiCuSil Composites	ZnO
Al_2O_3/Al Composites	Kaolin
Al_2O_3/Mo Composite	Stabilized Zirconia
	Mullite
Thick film, pastes, polymers & Epoxies	Silicon Nitride, PMN (In development)

Fab@Home

Fab@home has the goal of creating a low cost rapid-prototyping machine, and was created by Cornell University after being inspired by the success of the RepRap project[17]. However, unlike RepRap there is no focus on self-replication, instead their aim is just to get as many people as possible to use so called “fabbers”[18].

Rather than a deposition tool specifically designed to use thermoplastics, two syringe-based extruders are typically employed to enable the Robocasting process, shown in Figure 2.11. The tool consists of a NEMA 8 stepper motor, with a rotor mounted lead nut. A non-captive lead screw is then driven by the motor to drive a piston contained within the employed 10cc syringes, capable of producing a maximum force 90N.

Evan Malone, the lead developer in the Fab@Home team, initially investigated the use of a pneumatically powered dispensing system. However, this approach was abandoned as it was said to be, “tricky to find the right combination of nozzle diameter, material temperature, and dispensing pressure and pullback vacuum to use”. Therefore Malone argues that a volumetrically controlled system is more suitable to the Robocasting process.

A pneumatically controlled system requires that each material and nozzle combination would require a different set of operating parameters. However, pneumatic systems have a substantial advantage dealing with unwanted air which may become trapped within the pastes during loading. It is logical that the exact volume of air trapped will vary between pastes. Therefore when implementing a volumetrically controlled system, a preload would be required to enable deposition at the required rate, which would vary from build-to-build. Furthermore, pneumatic systems are used extensively in the dispensing industry, with many commercial systems available that deal with many of the same issues. Subsequently to the release of the Fab@home paste deposition tool, Makerbot and others have developed pneumatically driven paste extruders, in addition to the prior work of Cesarano, which would indicate that Malone's argument is invalid.

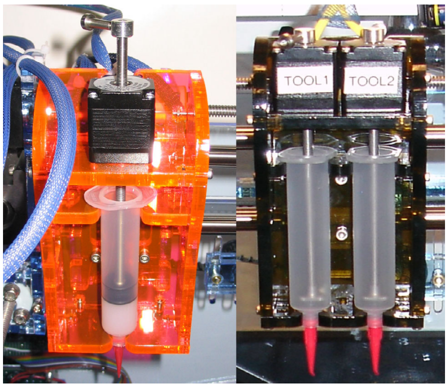


Figure 2.11: The Fab@home syringe tool[19].

2.1.6 Freeform Fabrication of Complete Electromechanical Devices

Perhaps the most relevant and comprehensive work into functional multimaterial AM components was undertaken by Malone *et al.* In parallel to the development on Fab@home, they looked to develop building blocks to enable the freeform manufacture of three dimensional, functional & electromechanical systems.

Printable Zinc-Air Battery & Electrically Conductive Flexure Joints

Whilst the manufacture of planar thin-film cells had already been achieved by Power Paper ltd, Malone's achievements represent the first example of a freeform three dimensional energy storage device. . Further, it is the first instance of a techique that is

Table 2.4: Key Printed Zinc-Air Cell Component Composition [20]

Component	Material
Electrolyte	8 Molar solution of potassium hydroxide and distilled water
Negative Terminal	Paste of methyl cellulose with copper (99% purity 2-5 μm) or silver (99% purity 1μm)
Anode	Slurry of electrolye with zinc (97.1% purity, dust) and surfactant
Separator	Paper, Rescor 740 insulating ceramic foam
Cathode Catalyst	Slurry of carbon black, manganese dioxide (MnO_2, 80-85% purity)
Cathode	Air
Positive terminal	Paste of methyl cellulose containing nickel (99% purity, 325 mesh), or copper or silver

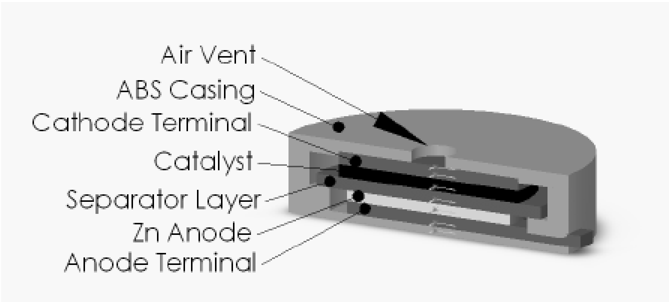


Figure 2.12: Cross-section of the freeform fabricated printable zinc-air battery[20]

potentially capable of harnessing some of the major benefits of additive manufacturing such as complex geometry. Table 2.4 highlights the key materials used in fabricating the device.

As part of the work conducted, Malone entered into a process of optimising the basic anode and electrolyte chemicals and concentrations in order to ensure maximum performance. After several iterations, the optimum catalyst compromised 50% MnO_2, 44% 8M KOH, and 6% carbon black, with the separator layer consisting of 8M KOH. The final design is shown in Figure 2.13.

In addition to optimising the materials utilised for the final cell performance, perhaps more relevant are the considerations taken in order to improve the extrusion performance. For the required conductive material, Pb-Sn solder was ruled out due to incompatible cell chemistry. Experiments were conducted mixing Methyl cellulose in 1:1 ratios by mass with Cu, Ni, and Ag powders [21]. For the separator material, sur-

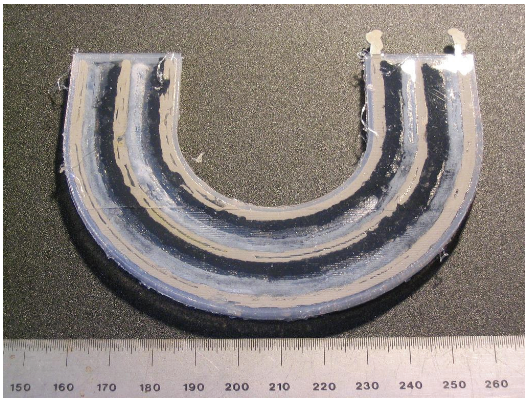


Figure 2.13: Freeform Fabricated Battery. Note the complex geometry[20]

factant, an additive to lower the surface tension, was added to several of the utilised materials to enable extrusion.

Qualitative experiments with methyl cellulose (MC) and metal power composite pastes reveals the dehydration of the MC gel may lead to shrinkage and cracking of the deposited paste, and also that adhesion to the substrate substantially deteriorates after dehydration. It is observed however that at no point has Malone investigated optimising the adhesion/joint between neighbouring materials through neither their respective geometries nor the effects of temperature that had been deemed critical by Cesarano.

During fabrication experiments, Malone notes that a calibration process was undertaken for each material. This involves identifying a suitable syringe tip: a plastictapered tip for viscous homogeneous and stainless steel parallel needles for multi-phase materials,though the reasons for this distinction are not elaborated on. Equally, orifice diameter was also varied, with increased sizes used for more viscous or phase-separation-prone material. Where possible, the smallest orifice diameter was chosen through which a material could be reliably extruded. Using this setup, estimates for key extrusion parameters were made, and iterated with the use of a test pattern until optimum results obtained.

When designing for this method, a key factor is that road height, established using the iterative process previously described, between material types may not necessarily match. Thus, when objects are sliced by the controlling software, no paths were generated for objects shorter than half the road height. Additionally, voids may occur due

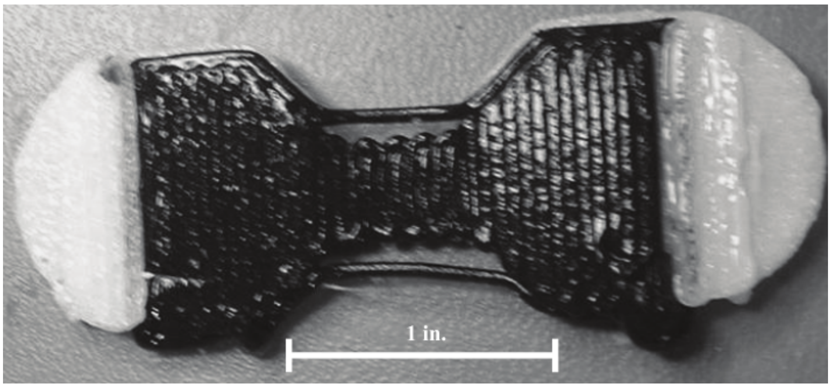


Figure 2.14: Freeform Fabricated ABS thermoplastic and silicone elasomer flexture joint[20]

to height mismatches between neighbouring materials on adjacent layers.

Building on this work utilising carbon black to enable electrically conductive components, Malone investigated the manufacture of electrically conductive flexure joints. The joints consisted of ABS rigid end members, and a 1-part room-temperature vulcanising (RTV) silicone as the flexible joint. Carbon black was utilised to sufficiently increase the silicone's viscosity such that it was freestanding upon extrusion. The device was shown to carry sufficient current to light an LED (10mA), but proved too fragile to survive real world use due to cracking and detachment of the conductive paste.

Electroactive Polymer Actuators

Further elements of Malone's library of compatible elements to produce electromechanical systems are actuators. At present substantial research has been done into the field of active materials, capable of changing shape, volume or some other property in response to a signal. Malone concluded that whilst such materials exist, many are not compatible with the fused filament fabrication process implemented[20].

Given the materials used in FFF, components have lower stiffness when compared to subtractively manufacture parts, all materials that offered a high stress output but at a low strain were removed. Equally, the device needed to be compatible with the other components developed for Malone's element library. Comparing these constraints to the proposed polymer properties leaves two potential material types, conducting polymers (CP) and Ionmeric Polymer-metal Composite Actuators (IMPC) [22].

Malone's observes that conducting polymers are "appealing", due to previous success in academia in printing electronics and sensors with them. A major difficulty encountered was the requirement for the actuator to function in air. Malone noted that to achieve air-operable actuators from conducting polymers, electrolyte must be used to enable their activation. Using a sample of P3OT (poly(3- octylthiophene-2,5-diyl), a film was cast onto a PTFE substrate, and allowed to dry. The actuation of this, both in an electrolyte and when sandwiching an electrolyte for in-air operation was proven, although the device took in excess of four minutes to actuate.

Ionmeric Polymer-metal Composite Actuators, are typically fabricated using a complex process and are fundamentally based on a solid membrane usually used in proton-exchange-membrane fuel cells. . These membranes typically have proton-bound to anions within the polymer chains. For actuation, these protons are replaced with others to improve actuation properties, and the membrane surfaces are soaked in metal salts, before the salt is reduced to provide an electrode. A voltage across these electrodes enables actuation. However, this process does not lend itself to freeform fabrication due to the reliance on the premanufactured proton exchange membrane, which is beyond the capability of present AM technogies. . A process previously developed was therefore utilised to enable the manufacture of IPMC actuators from a dispersion of Nafion particles in a solvent. Several materials were investigated for the required electrode, including conductive polymers, silver grease and metal powders. It was found that most of the materials suffered from chemical incompatibility, or contraction during evaporation of the solvent from the Nafion layers. However, some success was obtained when utilising a mix of Nafion, flurosurfactant and silver powder.

After these initial investigations, a series of experiments were conducted to improve the process of creating the Nafion IPMC actuators described above to enhance their performance and dispensability. In addition, a process was developed to enable the deposition of materials into an RTV silicone container onto which IPMC materials

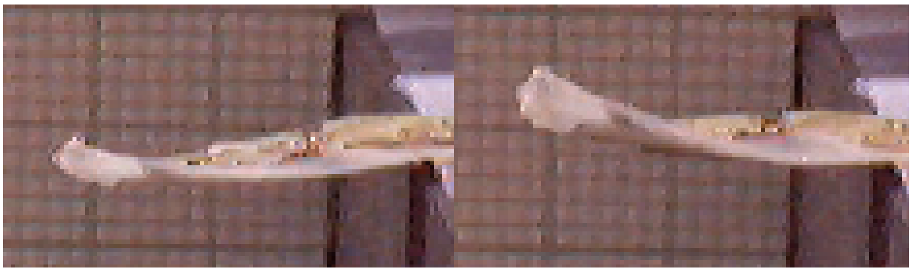


Figure 2.15: Actuation of annealed Nafion/Hydrin Blend. Elapsed Time 45 seconds

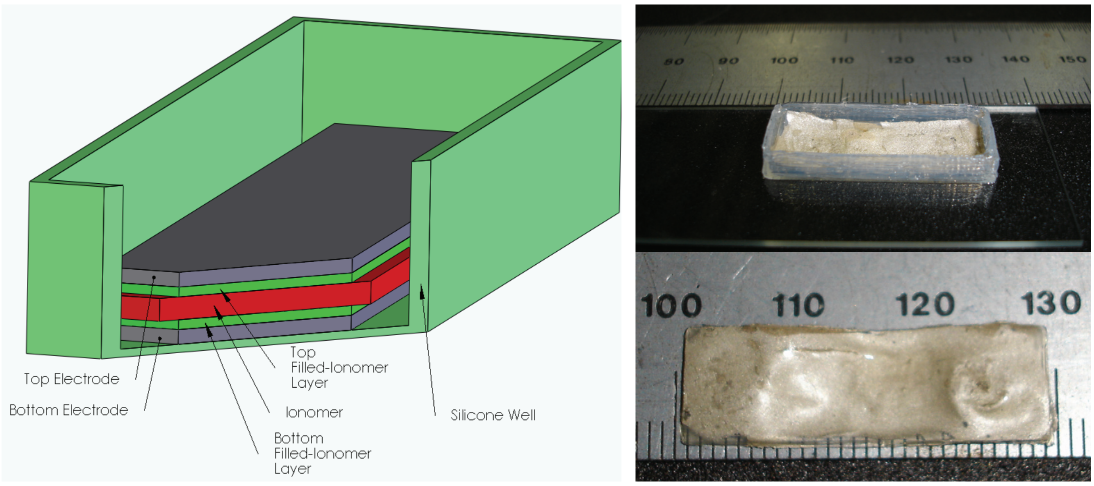


Figure 2.16: Freeform fabricated IMPC. Shown is a cutaway CAD model (left), IMPC in its silicone well (top right), and after hydration and removal (bottom right)[20]

were cast.

In order to deposit liquid materials into wells contained within this silicone , the manufacturing planning software needed to be extended. Typically for AM process, parts are always created using the same layer height for each layer, and each layer is completed before the next begins. Up until this point, this had also been true for Fab@Home. Using a technique called “backfill deposition”, the silicone wells were given a greater priority than the surrounding materials. Thus, these wells could be completely manufactured before the extruder nozzle was lowered back into the well to enable deposition of the surrounding materials in a process similar to casting. The final manufacturing process enabled the production of the first ever freeform fabricated IPMC actuator. The device was capable of operating continuously in air for more than four hours and over 3000 cycles.

Freeform Fabricated of Organic Electrochemical Transistors & Relays

The achievements detailed thus far have focused on devices that enable the movement or flexure of mechanical system, through providing power, actuation and the appropriate electrical connections. However, if we were to study the electromechanical devices used in everyday life, most would be impossible without the appropriate control system. Therefore, a 100% printable transistor is a major step forward. Whilst printable transistors have been previously produced using ink-jet printing, Malone sucessfully demonstrated fthe first instance that a transistor was printed using solid free-form fabrication [23].

An Electrochemical Transistor (ECT), is unique in the field of organic electronics, in that the fundamental process is dependent on a electrochemical reaction, triggered by an applied voltage, to turn the device on and off. This enables the operating voltages to potentially remain under 1V, and also ensures the device is not heavily sensitive to film thickness or any other dimensions[3] . Thus the lack of accuracy required makes ECTs an ideal candidate for an solid free-form fabrication transistor.

Whilst relays have previously been manufactured partially using AM in combination with electro discharge machining[24], Malone's efforts focused on the creation of a relay solely using solid free-form fabrication without manual assembly[25]. The device built on prior work conducted in the manufacture of Malone's IMPC actuator. In essence the relay utilised the IMPC to selectively close or open an electrical circuit by breaking contact between electrically conductive surface electrodes. The housing of the device was manufactured out of Silicone RTV, along with an IMPC mould which would later be used for casting of the IMPC materials. The materials investigated for other components of the relay are detailed in Table 2.5.

A significant difficulty, for which no solution was achieved, was that the IPMC material cast poorly in the housing material. Thus, IMPCs produced tended to have "thick and cracked" rims, which resulted in anode to cathode shorting and irregular material

[3] Roadwidth produced by a fab@home is limited to a resolution of 250micrometers

Table 2.5: Table describing materials investigated for use in Malone's solid free-form fabrication electromechanical relay [25].

Component	Anode, Cathode & Load Contacts	IMPC electrode
Materials	Conductive carbon cement, silver paint, silver-filled silicone RTV	Carbon black filled Nafion composite, Thermoplastic rubber/silver colloid composite, Ag-nanoparticle filled Nafion 0.7-1.3 um silver powder filled Nafion

layer thickness. Therefore the IMPC only produced low output force, and had poor switch performance. Whilst the creation of a relay was possible after a substantial amount of material and design optimisation, the performance of the device was poor, with a load/input current gain of 1.05. As such, further work is required investigating improvements to IMPC casting, and the associated housing and actuator materials. Once again, the IMPC material was cast onto a substrate at room temperature, despite the prior work of Cesarano showing this the temperature of the substrate has a substantial effect of cracking and deposition quality. Therefore, the author of this report believes implementing such a technique would offer substantial performance gains.

2.1.6.1 Rapid Prototyping of Electronic Components (RPEC)

In 1944, a British engineer named John Sargrove designed an automatic radio production line using a process he called ECME (Electronic Circuit Making Equipment) [26]. At the time, radios were still very expensive, and he required a method to reduce the labour costs associated with manufacturing and assembly. This led Sargrove to develop an early form of integrated circuit. His circuit was based around a piece of Bakelite that contained most of the radio's electrical components. The Bakelite was moulded, to contain a series of channels on each side (Figure 2.18). These channels were then filled with a zinc alloy to connect all of the electrical components contained within the Bakelite. As a result production costs fell dramatically whilst increasing production

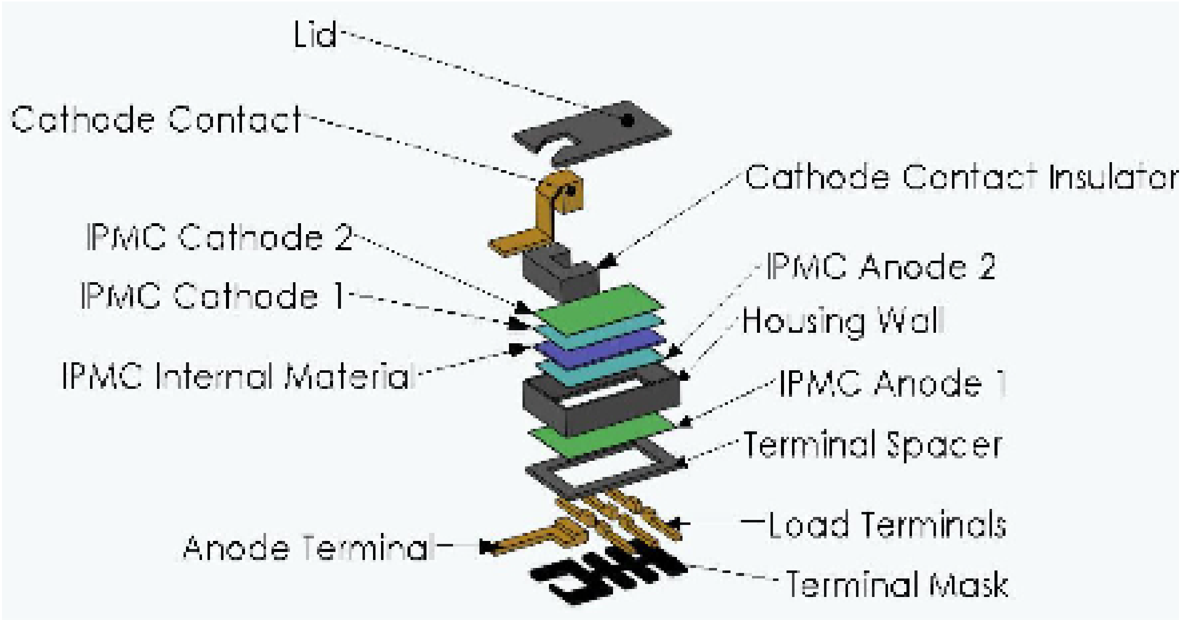


Figure 2.17: Solid Free-form Fabrication Electromechanical Relay

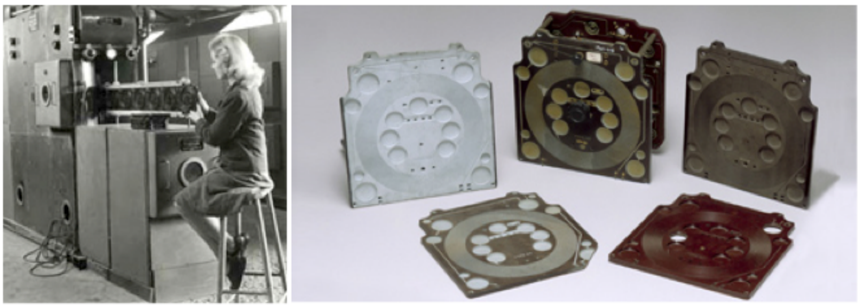


Figure 2.18: ECME Production Line (left) & the ECME Bakelite Chip [26]

capacity.

Inspired by Sargrove's work on ECME, Sells developed RCME techniques to allow the rapid prototyped ABS circuits (instead of the Bakelite circuits in ECME) with the aim of allowing RepRap to manufacture PCBs[27]. However, Sells required an alternative conductive material, as ABS has a lower melting point than that of zinc. Wood's metal is a toxic alloy of tin, cadmium, lead and bismuth which possesses a very low melting point of just 70°C. Sells' work focused on evaluating several methods of depositing the Wood's metal. The most successful of these involved molten distribution, whereby the alloy was melted and injected using a syringe for deposition. At first, Sells attempted to heat the syringe before injecting the material. However, this technique was inadequate, with the material freezing in the nozzle just twenty seconds after filling. Sells

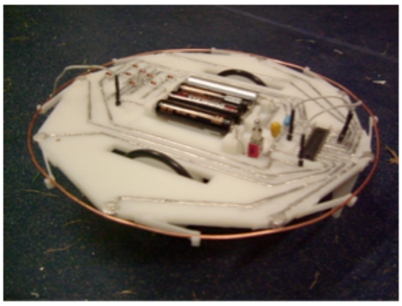


Figure 2.19: Robot manufactured using RPEC techniques [28]

iterated the design, by implementing a "jacket" of hot air around this syringe during the extrusion process. This was sufficient to prevent freezing. Upon extrusion, the alloy had the tendency to form molten droplets; this was attributed to the high surface tension of the material, and led to the material being difficult to manipulate once extruded. Whilst the molten material was injected into a rapid prototyped substrate, the injection process was done manually by hand. Nevertheless, Sells' research culminated in the manufacture of a working robot, demonstrating the capability of RPEC [28].

Subsequently, Sells work was furthered by the author of this report, by automatically depositing low melting point solders automatically into an ABS substrate. The extruder utilised consisted of a stainless steel needle with a 1.3mm diameter orifice, heated with nichrome wire in a similar fashion to standard RepRap thermoplastic extruders. A key finding was that the solders must be solid i.e. without flux. The presence of flux would enable the extrudate to separate into sections of conductive solder, and non-conductive flux rendering the track useless[29].

After testing several materials, 60/40 PB/Sn solder was utilised due to its ease of availability in filament form. Interestingly, the melting point of the alloy (240°C) was substantially higher than that the ABS substrate (105°C). Therefore the process was enabled by the fact that thermoplastics generally have a specific heat capacity roughly 10 times bigger than that of the alloy. This results in less heat transfer to the thermoplastic than was initially expected, and thus only minimal deformation occurs to channels contained within the substrate providing wall thicknesses were greater than approximately 1mm.

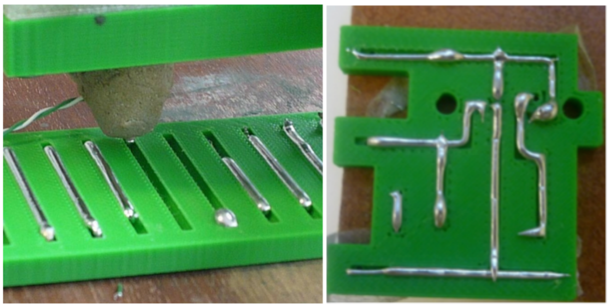


Figure 2.20: Example of RCME build quality using 2.6mm channels (left), and the optoswitch PCB (right)[29]

Whilst reasonable build quality (Figure 2.20) was obtained for channels that were 2.6mm in width, this was deemed not sufficiently intricate to allow for useful circuits. After several iterations of the extrusion parameters, the device was capable to depositing alloy into 1.3mm diameter channels reasonably reliably, although build quality was reduced. Figure 2.20 shows a simple PCB manufactured that functions as an optoswitch circuit board. The device replaced another PCB from within the RepRap machine that created it, and functioned successfully.

It was concluded that further work needs to be undertaken to reduce the effects of surface tension though reducing the extruder orifice diameter, in order to enable more complex circuits and smaller components. Equally, it was somewhat tricky to solder in components after the PCB was manufactured. It is speculated that a rapid prototyped holder could be design to secure components within the plastic substrate during the production of the PCB, ensuring post soldering is not required.

2.1.6.2 Voxel Based Additive Manufacturing

As outlined above, frequent difficulty obtaining the correct rheology and extrusion characteristics was encountered by Malone for materials when using Robocasting. Whilst substantial efforts have also gone into fabrication using inkjet methods, even greater restrictions are placed on the material composition[30]. Therefore a substantially different approach to 3D printing has been proposed by Gershenfeld [31].

Gershenfeld's concept is strikingly similar to von Neumann's original proposals for

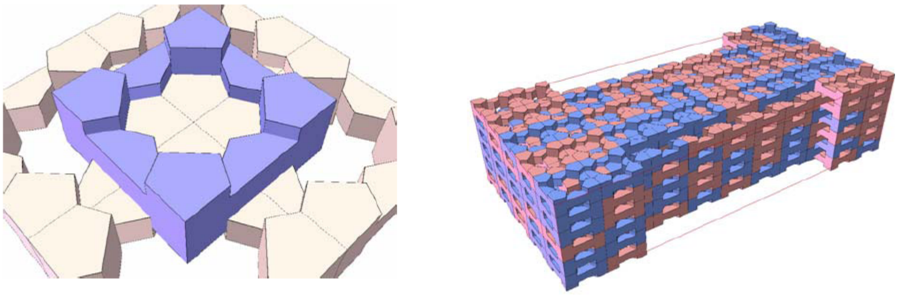


Figure 2.21: 2.5D Interlocking square voxels (not self-assembling). Finite Element analysis used to enable virtual tensile test(right)

a kinematic replicator, except with an emphasis on producing any functional component, rather than self-replication. In essence, the process is a rapid assembler, capable of positioning and bonding pre-manufactured voxels(a term borrowed from computer graphics). The manufacture of such voxels would be achieved using traditional manufacturing technologies, and thus negates the difficulties with material rheology. In addition, it is proposed that “smart” voxels may be produced allowing active components such as transistors, photovoltaics and micro valves.

A key strength of the process is the ability to control the geometry of the voxel itself. A substantial investigation by Hiller[32], reveals that by controlling the shape of the voxel, they may automatically self-align and interlock during the assembly process. This potentially enables the fabricated components to more be accurate and repeatable than the positioning system of the 3D assembler.

Further still, the technology is capable of altering material properties using a variety of different methods. A substantial investigation was undertaken by Hiller to determine potential techniques. Hillier’s research, due to the early stages of the technique, was based on finite element analysis to enable a virtual tensile test.

Interestingly, substantial variations in material properties and failure modes were possible, even for single material structures. Rightly, Hiller assumed that the manufacturing of the voxel would be subject to tolerances. It was found that as these tolerances were relaxed, the elastic modulus continuously decreased, and the initially brittle fail-

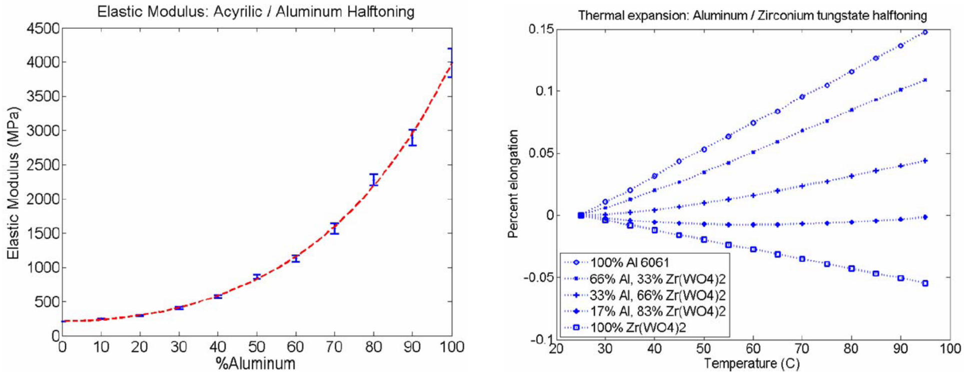


Figure 2.22: Graphs showing the effect of half-toning for an aluminium/acrylic based structure on elastic modulus (left), and for a aluminium/zirconium tunstate structure on thermal expansion coefficient(right).

ure mode became more and more ductile. The effect was substantial, reducing the elastic modulus by approximately 66%for an error of just 10μm.

Given the sensitivity to error, the author of this report concludes that to achieve a precise value of a given material property in practice therefore would be, whilst possible, expensively prohibitive to manufacture the quantity of voxels needed to the accuracy required. Further still, the number of voxel types required to give continuously variable material properties would be such that printer design would be unnecessarily complex. Thus, Hiller's efforts shifted to multiple materials.

Hiller found that by utilising a technique traditionally used in reprographics known as half-toning[4], a near continuous variation in the bulk material properties may be produced, just by setting the desired percentage of each material, and randomly scattering the voxels within the component in the desired ratios.

Hiller found that using these techniques for a combination of acrylic and aluminium voxels, the elastic modulus varies exponentially, as the amount of aluminium is increased (Figure2.22). Perhaps more interestingly, was work undertaken combining aluminium, a material with a positive coefficient of thermal expansion (CTE) and zirconium tungstate (negative CTE). For a specific ratio, a material test sample was produced that was predicted to have a nearly negligible thermal expansion or contraction.

[4]A technique whereby greyscale appearance may be generated only by varying the size and placement of black pixels

One final possibility was investigated by Hiller as a method for adjusting bulk material properties, altering the material micro-structure. Half-toning results in near isotropic material properties. Through the grouping several voxels of different materials into a "super voxel" and then tiling this throughout the part, various anisotropic properties are possible depending on the super voxel configuration; even if the material ratios remained constant. For some configurations, an elastic modulus in excess of three times the value in the perpendicular direction was achieved, resulting in significant anisotropy.

In addition Hiller also demonstrated an auxetic micro-structure created using a similar technique, just using aluminium and acrylic voxels. Using this structure a Poisson's ratio of -0.63 was achieved.

The author contends that whilst Hiller's results are fundamentally interesting, they are not suitable for practical implementation. Firstly, it seems that the difficulty of producing an "active" or smart voxel has just been offloaded to an external process. Secondly, it has been demonstrated that manufacturing tolerances of these voxels are critical, and thus given the number required, the process is likely to be prohibitively expensive. However, it remains to be seen whether the micro-structures demonstrated could be manufactured using traditional AM techniques, potentially offering similar results. Further still, substantial variations in bulk material properties were shown by adjusting joints between neighbouring voxels. Potentially this effect could be replicated in mechanical joints in multi-material structures created using more conventional multi-material AM techniques.

2.1.6.3 Objet Geometries

Whilst multiple materials has been used by commercial AM companies in order to improve the AM process e.g. infiltration of porous material with adhesive for solvent jet printing, the use of multiple materials to provide increased functionality by commercial vendors has been somewhat limited The research mentioned thus far was done in academia. The only company at the time of writing to enable functional multiple mate-

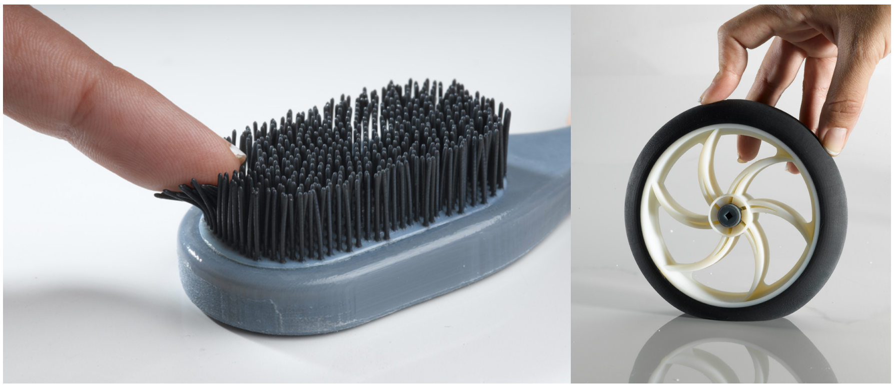


Figure 2.23: Samples produced using the Objet Connex Family of 3D Printers. Tooth brush model with a rigid handle, and flexible bristles (left) and a flexible tyre on a rigid rim (right)[10]

rial parts is Objet Geometries[10]. Example multimaterial components manufactured using an Objet Connex system are shown in Figure 2.23

Objet utilise the Jetted Photopolymer process to provide a mechanism to deposit droplets of photocurable resin[2]. Where Objet's techniques differ from others is that the resin can be mixed with differing ratios of curing agent to result in polymers with different shore hardness ratings. Further, software developed by Objet enables varying shure harnesses throughout different regions of the part. A typical example for a specific curing agent and photocuring resin offers discrete variations in shore hardness from 40 - 95, and a corresponding change in tensile strength from 1 to 49Mpa [33].

2.1.7 File Formats

With the advent of the multimaterial AM techniques previously outlined, a new challenge was imposed on the industry: how to digitaly store CAD data such that information regarding mesostructure, material properties and other information may be recorded whilst remaining compatible with existing CAD systems? To date, the STL file format has established itself as the dominant file format for the AM industry in part due to its compatibilty with all major CAD systems and 3D printers. However, the STL format only contains information regarding the surface of a part, and thus offers no method for representing internal colour, texture, material properties etc. The surface of a part is represented in a list of unstructured triangles, with each triangle being represented by 12 floating-point numbers. However, it is contended by Hiller and Lipson [34], that the format has not gained traction due to its technical merits, but because of its simplicity.

One consequence of the method implemented is that each vertex must be stored repeatedly, once for each triangle that shares the vertex. This frequently generates voids in the surface owing to rounding errors. Thus, STLs often require pre-processing before being used in slicing software employed by AM machines in order to be usable.

Several alternative file formats have mean proposed for use by the AM community these are described in Table 2.6, which is based on an excellent summary by Hiller & Lipson [34]

In addition to those outlined, two proprietary formats also exist that enable the storage of colour/material information. These are Zcorp's ZPR (colour only), and Objet's Objdf (material/colour). Typically, STLs or other formats may be converted to these types using the relevant vendor's software. However, given the proprietary nature of these formats, utilising these with other vendor's or open source machines is not possible. Given this issue, in parallel with the aforementioned problems due to rounding errors, an alternative is required.

At present, the AMF format is being considered by ASTM to become the de facto replacement for STL[34] which allows the inclusion of colour, material properties etc. The AMF format is based on the Extensible Mark-up Language (XML), and thus new features may be added to the format as required.

Further still, AMF is capable of defining geometry as a mesh, and thus converting between STL and the proposed format becomes fairly trivial. Equally, material properties may be a graded to enable a continuous variation throughout the part. However, CAD software does not currently exist that is compatible with the format. Moreover, and rightly so, the format aims to be independent of vendors and AM systems. Thus material properties such as Young's modulus are exactly defined, and so a substantial

Table 2.6: File Formats Proposed for use by the AM community

Format	Description	Advantages/Disadvantages
X3D(VRML)	Mesh based file formatted intended to enable the viewing of 3D content on the Internet	Includes information about 3D surface and its colour. However, also contains data intended for rendering such as transparency, animation etc. No provisions for defining multiple materials
STEP	Format intended for solid-model representation using extruded and swept solids, wire-frame and boolean modeling.	Complex
PLY	Format designed for use within the 3D scanning space by the storing of polygon meshes.	Capable of storing data relating to texture and colour. No definitions of material or micro-structure
SAT	Widely used for boundary representation objects in CAD packages	Format is based on the description of an objects internal topological data structure. This insures its difficult
OBJ	Mesh model format, Widely used for 3D modeling	No definitions of material or micro-structure
DXF	Widely used in CAD for 2D drafts, although capable of defining 3D triangle meshes	Intended for 2D use, therefore remain best suited for such.
3DS	Triangle mesh based format	Capable of colour and texture data. Limited to defining 65536 triangle and vertices's
SLC	Represents a 3D object by a series of 2D slices separated by fixed intervals in the Z plane.	A fixed Z spacing will inevitably cause problems between AM systems, ass layer heights may vary.

```xml
<?xml version="1.0"?>
<AMF>
  <Palette>
    <Material MaterialID = "0">
      <Name>StiffMaterial</Name>
    </Material>
    <Material MaterialID = "1">
      <Name>FlexibleMaterial</Name>
    </Material>
  </Palette>

  <Object PrintID = "0" units = "mm">
    <Mesh>
      <Vertices>
        ...
      </Vertices>

      <Region FillMaterialID = "0">
        ...
      </Region>
      <Region FillMaterialID = "1">
        <Triangle V1 = "5" V2 = "6" V3 = "7"/>
        <Triangle V1 = "5" V2 = "7" V3 = "9"/>
        ...
      </Region>
    </Mesh>
  </Object>
</AMF>
```

Figure 2.24: AMF file format[34]

amount of research is required to investigate exactly how these properties are achieved for a given solid free-form fabrication process.

Chapter 3

Multi-Material Functonal Components

3.1 Summary

Firstly, development needed to enable the utilisation of multiple extruders to allow multimaterial deposition. For simplicity, it was elected to develop the existing RepRap Mendel design rather than to develop a head changing system.

Secondly, development of extruders and the associated materials was required. Fused filament fabrication and Robocasting together were deemed sufficiently versatile and practical to manufacture electro-mechanical components owing to successes already achieved in the RepRap and Fab@Home projects. Thus, research was embarked upon to implement both the Robocasting and FFF process in parallel using the aforementioned developments to the Mendel machine.

To enable the Robocasting process, two fundamental paste deposition methods were evaluated experimentally. A volumetrically controlled method was shown to lack repeatability, However, the alternative pneumatically driven process was shown to be repeatable to within 4%, within the requirements of the process.

Consequentially, these developments enabled the manufacture of a multimaterial com-

ponent comprising of both PDMS and PLA To the author's knowledge, this is the first instance of Robocasting and fused filament fabrication processes beeing combined, and thus it has been shown the test setup implemented is fit for its purpose. Therefore, research has begun, and is ongoing, on implementing the required functional materials to manufacture electro-mechanical components. Thus far, preliminary investigations have taken place developing magnetic and conductive materials through the addition of active powders to create a composite paste. These materials have shown promising, but at the time of writing they have not been utilised in building an actual component.

3.2 Design Brief

A new RepRap 3D printer, or substantial modifications to an existing printer, should be designed to manufacture multimaterial 3D complex electromechanical components using solid free-form fabrication processes. The printer should be considered a test bed to:

• enable the characterisation of the implemented solid free-form fabrication processes

• be sufficiently flexible to utilise the materials required for the manufacture of complex electro-mechanical components.

3.3 Process Selection

As has been previously outlined, Robocasting has already been demonstrated to be capable of depositing a wide variety of active composite polymers and ceramics, and has already been shown capable of producing crude electromechanical components in a low cost, simple fashion. Therefore, this process also offers the best prospects of manufacturing more complex components within the context of producing a self-reproducing AM machine. However, with fused filament fabrication already being shown to be able to produce approximately half of the components for such a machine in a low cost manner, discounting FFF is unwise.

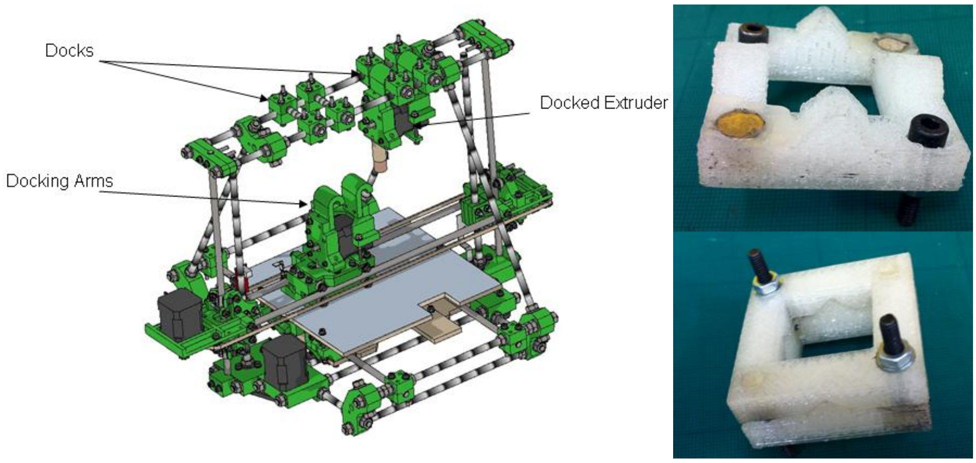


Figure 3.1: Head changer concept 1(left) magnetic carriage, undocked (upper right) and docked (lower right)

Equally, the author would contend that the FFF process benefits from ease of material handling, and being capable of hundreds of hours of operation unattended. Conversely, the use of large syringes in Robocasting is impractical from a machine-design point of view (weight, volume required in the Cartesian robot etc). Therefore, it is proposed the hybrid system would offer the most versatility whilst remaining practical; utilising FFF for large components where no specialist properties or active functions are required, and using Robocasting where such attributes are needed.

3.3.1 Cartisian Robot Development

Three concepts were considered for the Cartesian robot. Firstly, a head changer proposed by Sells for implementation with minimal modification to the standard RepRap design was considered. The idea consisted of a series docks secured to the top gantry of the Mendel design. It was proposed that a magnetic attachment system would enable each extruder to couple to the Mendel X carriage when needed. These fundamental ideas have been developed by the author into the concept show in Figure 3.1

The author observes that whilst this method allows for a head changer with minimal modifications to the standard frame, a substantial loss in build volume in the Z direction is inevitable. The concept is dependent on the operating extruder being able to operate directly underneath the docked extruders. Given that each standard Mendel extruder is approximately 125mm tall, at least this value will be lost from the Z build volume; leaving just 15mm build height at standard dimensions without allowing for clearance for filament feed and cabling.

Clearly, the mechanical design would need to be enlarged in the Z direction, which, whilst possible, would entail substantial work as this would also imply increasing the Y build volume given the machine's equilateral prism design. Thus this approach was deemed too risky when coupled with development work that would be needed to ensure repeatable and accurate docking of the heads. Further, the dimensions of the Robocasting extruder are unknown, thus this makes an integrated and complex concept such as this difficult.

One final alternative remains, a redesign of the extruder carriage. Given that support material is required for Robocasting, at least three extruders are required. Therefore, to avoid a substantial loss in build volume, the volume of each extruder must be reduced. Sells' previously postulated the implementation of a Bowden drive mechanism, whereby the filament drive is decoupled from the extruder itself, and the filament guided to the hot end by a stiff low friction tube [35].

Potential side effects of this approach include:

• Stretching of the tubing may affect print quality

• Increased motor torque needed to overcome friction

Despite these disadvantages, some limited testing has previously been conducted with some success [36]. Taking this approach would enable each extruder to take up less volume by allowing the drive mechanism to be external to the machine, and mounting three extruders simultaneously would be possible. In addition, height adjustment is already known to be critical for fused filament fabrication; therefore each extruder requires independent height adjustment that is not needed for head-changer-based concepts. A sketch detailing this approach is shown in Figure 3.2

Given the unknowns associated with Robocasting, an integrated approach such as the head changer concepts was thought to be insufficiently versatile to allow for modifi-

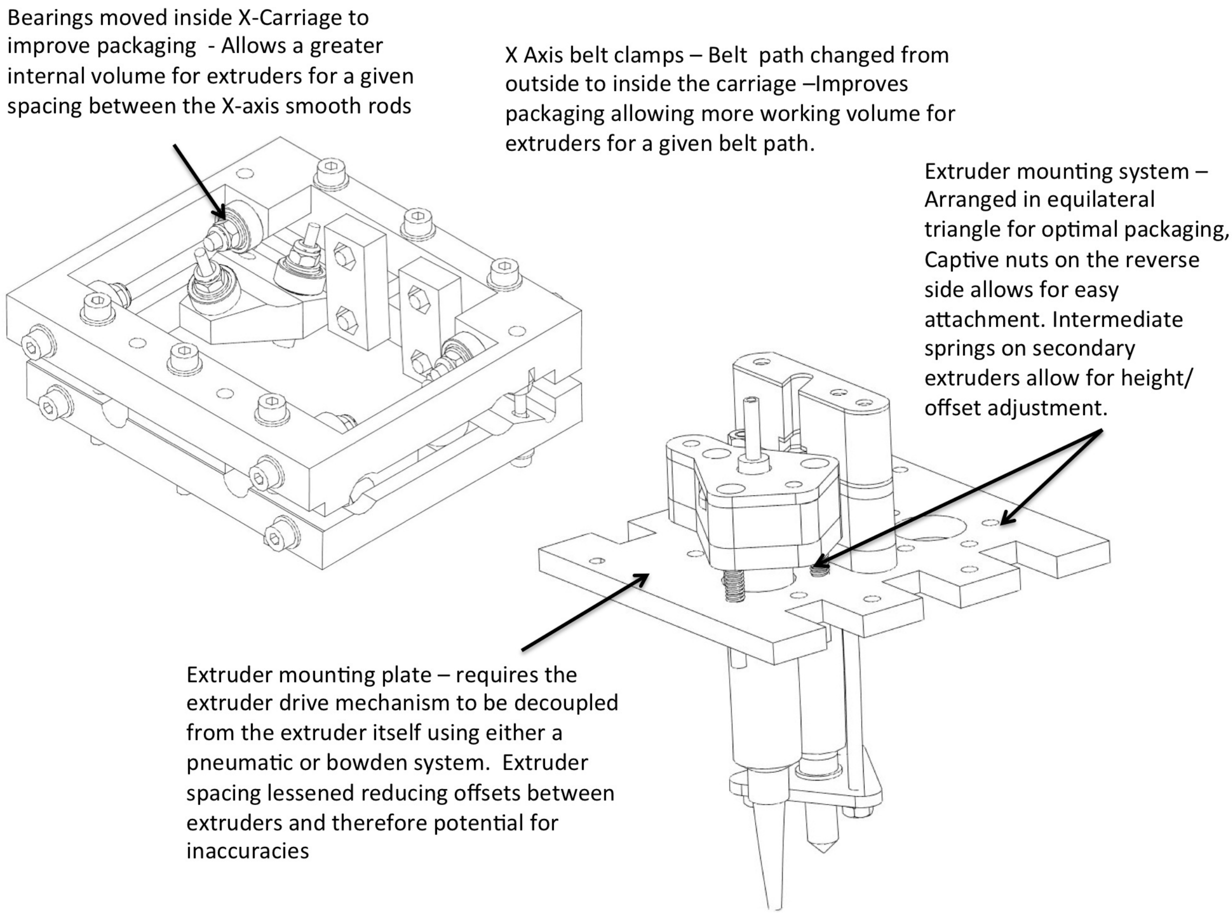


Figure 3.2: Multiple Extruder Carriage

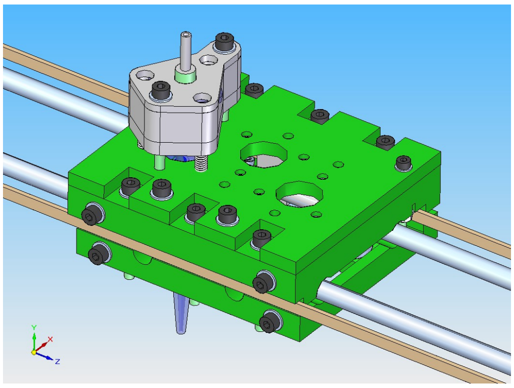


Figure 3.3: Implemented MultiExtruder Extruder Carriage

cations to the system as the process is developed. Therefore it was proposed that the Bowden approach would be best suited for research. The concept previously outlined was developed into the system shown in Figure 3.3. The design offers the capability of handling three extruders, providing their maximum diameter is 16mm. Given this, work transferred to developing a paste & thermoplastic extruder compatible with this system.

3.4 Thermoplastic Extruder Development

Following the concept outlined previously, a Bowden thermoplastic extruder was designed and implemented into the system, shown in Figure 3.4, based on the Bowyer's geared extruder. After a short amount of testing extrusion stopped despite the drive mechanism appearing to work correctly. It was found that the PTFE tubing, which was held using adhesive, was secured insufficiently at the extruder end of the system. Further development, based on the work of de Bruijn, was conducted to improve this joint by threading the outside of the tube using an appropriately sized die. A nut could then be used for fixing. However, despite this method working successfully for de Brujin [36], a similar failure mode to that previously described occurred again.

Subsequent testing reveals the walls of the PTFE tubing were insufficiently stiff and thus the thread disengaged from the nut. After changing the tubing wall thickness to 1.6mm, this problem has been solved.

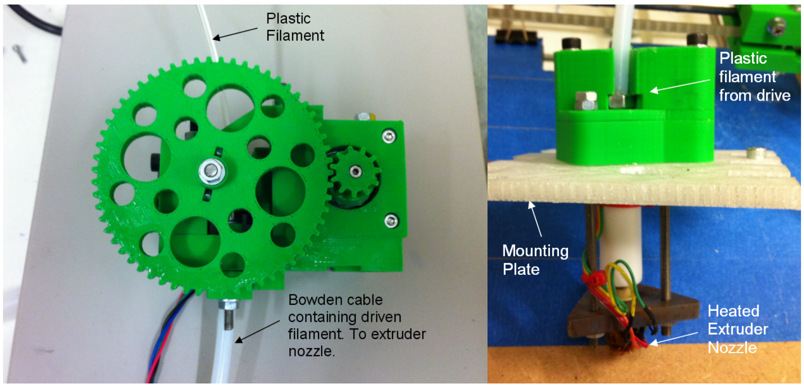


Figure 3.4: Thermoplastic bowden extruder drive mechanism (left) and nozzle (right)

Utilising this design, it was found that the extruder oozed substantially compared to standard RepRap designs. Whilst RepRap extruders typically ooze a small amount, reversing the filament a small distance at the end of a run typically solves this issue. However, increasing this reverse by nearly a factor of three, compared to direct-coupled extruders solved the problem in the above design. It should be noted that if the extruder is left at temperature for a long period (>20seconds), oozing can still occur. It is thought that utilising thinner filament may further ease these problems, by providing mode accurate filament control, although the risk of buckling under compressive load is increased.

3.5 Robocasting Development

As has previously been described, two techniques are prevalent in Robocasting: either pneumatic or volumetric control. The literature review established that on first appearance, both of these have their advantages and disadvantages. Pneumatically controlled systems typically deal very well with the inclusion of air in the deposited pastes, whereas volumetrically controlled systems are force independent, and thus should ensure fewer setup changes between pastes of different viscosity etc. Therefore, given this the lack of clarity in determining the optimal solution, it was decided to pursue each path independently.

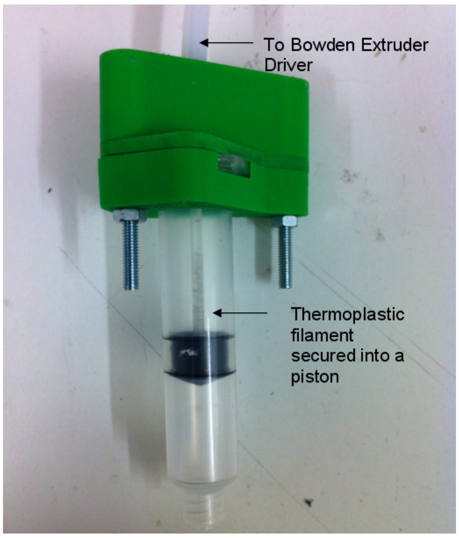


Figure 3.5: Bowden Paste Extruder

3.5.1 Volumetrically Driven Paste Extruder

In order to allow three extuders without a substantial loss of build volume and without a major redesign of the cartesian robot, it was required that all extruders needed to be very compact. Therefore, utilising a design where the motor was directly coupled to the piston, such as the Fab@Home system shown in Figure 2.11, was not an available option. A concept of Bowyer was to utilise the thermoplastic bowden drive mechanism described previously. Rather than feed the thermoplastic filament into a heated extruder nozzle, a piston was to be secured to the end of the filament, and in turn displace a paste in a syringe as shown in Figure 3.5. Naturally, this concept would reduce the stiffness of the overall system in the process. Given that the force required for extrusion for a given nozzle orifice would increased substantially as the syringe diameter increased, it was unclear at what syringe size this reduction in stiffness would become an issue.

During testing, it was found that a significant preload needed to be utilised in order to get the required flow rates. Equally, and like the thermoplastic designs, a reverse parameter was utilised to stop flow when required. For 3cc syringes, acceptable results were achieved, but it was deemed this volume was not suitable to produce usefully large components. Upon scaling the design to 10cc syringes, it was found that the preload varied from test to test by up to 50% to get the required flow rates. , .It was also found that if the drive mechanism slipped due to the high extrusion forces, this preload would be removed. This would result in a substantial reduction in extrusion rates and produce unsatisfactory results. Further, an incorrect filament feed rate could build up or remove the preload if even with the smallest error.

Given the lack of success with these initial experiments, this work was abandoned and work concentrated on the pneumatic concept.

3.5.2 Pneumatically Driven Paste Extruder

Breaking down the pneumatically driven systems described in Section 2.1.3 gives several areas of work:

1. Dispensing Components

2. A valve to control air flow

3. The mains air supply

Given the aim of creating a self-manufacturing machine, wherever possible, components and assembly were to be manufactured using FFF which RepRap can currently achieve. It was decided that manufacturing dispensing components and the air supply system required a degree of capability and accuracy not currently possible. However, a concept for creating a part self-manufactured valve was jointly developed by the author and Patrick Haufe [1], and is shown in its completed form in Figure 3.6.

The device consists of a dual shaft DC motor, with one shaft connected to a cam, and the other connected to an opto-switch flag (not shown). As the cam rotates, a spring is compressed, blocking and releasing air flow running through silicone tubing on the opposite side of the spring. The flag passes through an optoswitch to enable the RepRap software to know when the cam is at the points where the valve is open or closed.

[1] In addition, the firmware to control the device was developed mainly by Bowyer, in collaboration with the author

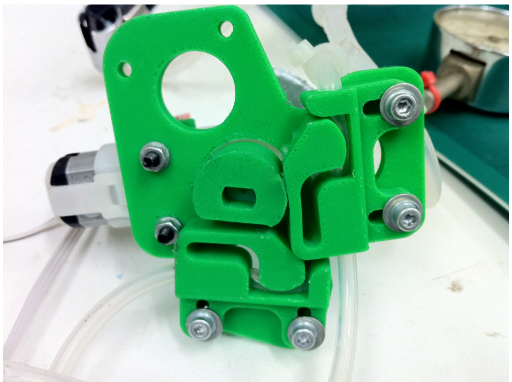


Figure 3.6: Rapid Prototyped Valve. All parts in green are produced using fused filament fabrication

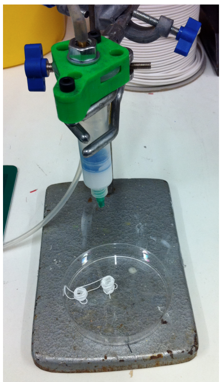


Figure 3.7: Pneumatic Paste Extruder Test Setup

Critically, the design does not simply disconnect the air supply in the off position. This would leave the syringe at an elevated pressure resulting in unwanted extrusion. A second valve is used to ensure that this excess pressure is release to the atmosphere reducing this unwanted material. In testing, the device has proved to be successful, and capable of functioning at pressures in excess of 2 bar (limited by air supply). Further, the time lag that is inevitable in the opening/closing action is easily accounted for in RepRap's software. Given the success of the valve, work shifted to investigating the repeatability of extrusion using the device.

Given the constant force nature of a pneumatically driven process, a series of experiments were conducted to establish the effect of externalities on volume flow rate .Utilising the test setup shown in Figure 3.7, attached to the valve previously described, the mass of polydimethylsiloxane[2] (PDMS), was to be recorded for a variety of experi-

[2]Henkel Unibond "super" bathroom sealant

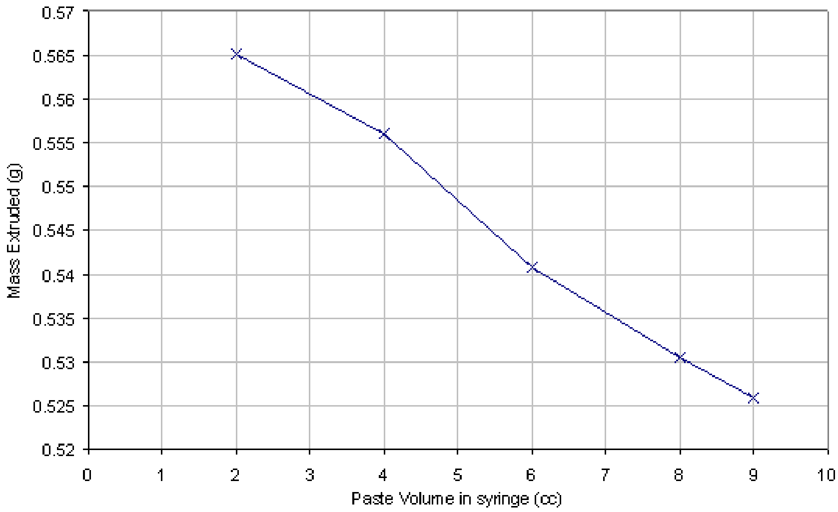


Figure 3.8: Graph showing variation in mass of PDMS extruded vs Volume of PDMS contained within syringe. Test conducted at 1.6 bar for 5 minutes

mental parameters. It was found that test to test variation due to different, although the same specification, pistons, tips, and syringe barrels resulted in a variation in the flow rate of 3%, with an average flow rate of 1.1cm^3/min at 1.6bar when utilising 18 Gauge (0.838mm ID) 2mm long steel tips and a 10cc syringe.

It is logical that the wall friction will vary as volume of paste contained within syringe changes. Given the constant-force method implemented, this change in friction will result in a change in the flow rate.. Figure 3.8 shows the result of an investigation into this variation, using the test setup previously described. It was found that the variation did not exceed 4% from the average under any circumstances. Further, Newton's law of viscosity states the anticipated reduction in wall friction should vary linearly with contact area, and therefore volume for a syringe of constant cross section. Thus, this linear reduction in wall friction should result in a proportional increase in flow rate with reduced volume in the syringe. It can be seen the results are broadly linear]matching expectations.

It is known that fused filament fabrication is an inherently forgiving process and flow rate variations of up to 10% can be accomodated whilst still producing acceptable results. Whilst Robocasting utilises a different extrusion method and materials, the fundamental process is similar to FFF. Further, the pressure during these tests was

Figure 3.9: An intermediate result whilst tuning the Robocasting process for PDMS (left) & the final build quality achieved (Right)

manually controlled by hand, and thus would account for some of the error

Given these facts, it was anticipated that the achieved results would be acceptable and therefore a pneumatic system was chosen to be favoured over the aforementioned volumetric system. Hence an iterative process was undertaken whereby known key parameters were empirically adjusted to give optimal build quality for the test setup previously descried. A description of these parameters along their optimal values may be found in Table 3.1.

Figure 3.9 shows an example of some of the results achieved during the empirical tuning process described. It can be seen that several “strings” are apparent at some of the edges of the part. This is attributed to the relatively high viscosity of the paste, and in-air non-extruding movements of the extruder “stirring” deposited material. It is anticipated that the results could be further improved if, before an in air movement, the entire extruder lifted a small amount to prevent this mixing. Neverthe-less, the final result shown was deemed sufficient to attempt a true multi-material part.

3.6 Combining the Robocasting & FFF processes to allow the manufacture of multimaterial components

At this stage of research, both thermoplastic and paste extruders had been independently implemented. However, work needed to be undertaken in order to allow for the control process to deal with each extruder simultaneously. The final test setup is show

Table 3.1: Critical Build Quality Parameters For Paste Extrusion

Parameter	Description	Final Value
ValveDelayForLayer(ms)	For the first time the extruder is used on each layer, the delay between opening the valve and starting to move the extruder head.	200
ValveDelayForPolygon (ms)	As above but for each sucessive valve opening for the remained of the layer	200
Valve Over Run (mm)	The distance before the end of a road sequence to close the extruder valve.	2
Extrusion Pressure (bar)	Pressure utilised during extrusion to enable the build of required parts	1.6
FastXYFeedrate (mm/min)	Speed at which the extruder plots. Other parameters exist that enable acceleration, these were disabled for Robocasting.	1000
Extrusion Height (mm)	The depth of each layer. Must be identical for all extruders	0.3
Extrusion Infill Width (mm)	Gap between in the zig-zag pattern used for fine infill on the exterior walls of an object	0.8
Extrusion Broad Width (mm)	Gap between in the zig-zag pattern used for course infill in the object interior	0.8
Extrusion Size (mm)	Width of extruded roads	0.8
Infill Overlap (mm)	Amount to overlap infill and outline. Ensures both are welded together.	0.2

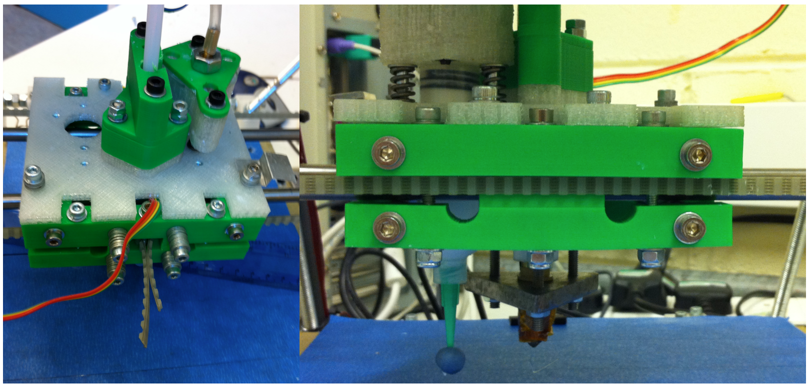


Figure 3.10: Multiple material test setup

in Figure 3.10.

Firstly, and critically, the question remained of exactly how to define a two-material part. Given the premature status of multimaterial file formats, and the lack of compatibility with existing software, implementing a fundamentally new format would be unwise. Therefore, utilising the STL format was the preferred option. It was decided that separate STL files were to define each material within the part. Fortunately the triangles that define the surface of a part are stored relative to a fixed origin. If designed correctly, this origin could be utilised to enable the software to be aware of where on material lies relative to another. This technique was implemented by Bowyer in the RepRap host software. In addition he also implemented a technique that enables all of the required part files, the relevant material and extruder information, and the relative position within the build volume within one file, known as an RFO (RepRap and Fab@Home Object) file [37]. The file is essentially a ZIP file ,containing the required STLs and a legend file of Extensible Markup Language (XML) to define the material and the position.

Secondly, the controlling software that generates tool paths based on this geometrical data was incapable of dealing with offsets between different extruders. Therefore, a simple Java post-processing program was by the author in collaboration with Gerrit Wyen to take account of this.

An attempt was made to create a simple cube, using PLA thermoplastic for the exterior, and PDMS for the interior infill. The produced part may be seen in figure 3.11.

Figure 3.11: PLA/PDMS Cube

Given the weak external shell and the PDMS interior, the walls of the part are capable of significant deflection (approximately 3mm); however it was observed that the part suffered from delamination at the corners. It is anticipated that this may be resolved by increasing the exterior wall thickness from its current value of 0.7mm

Further, it was noted that the thermoplastic extruder "oozed" substantially whilst the PDMS extruder was in use. Given the dimensions of this part, this was not an issue. However, for larger components it is likely the thermoplastic extruder may deposit unwanted material into an area of already-deposited paste. It is thought that either utilising thinner plastic filament, thus gaining more control, or alternatively reducing the extruder temperature when not in use will alleviate this issue.

Subsequently, the part shown in Figure 3.12 was manufactured. It is a pair of PLA tweezers with PDMS grips. In order to minimise the effect of unwanted oozing described previously, a small barrier was build around the tweezers, and thus prevent any unwanted extrudate from hitting the part during head movements.

It was observed during the manufacturing of the part that extrusion of paste stopped approximately 75% through the build. The nozzle was replaced mid-build, enabling the part to finish building satisfactorily. On closer inspection, it was discovered that the thermoplastic section build quality was poor, with several lumps of the surface of the part. Typically this isn't an issue given the stiffness of the thermoplastic extruder. However, for the paste extruder in this test, a tapered plastic tip was utilised to maximise the flow rates. This tip ran over these uneven areas and the nozzle orifice

Figure 3.12: Multimaterial Robocast & Fused Filament Fabrication Tweezers

deformed, leading to increased pressures being required for similar flow rates. Subsequently, steel tips have been utilised and so far, the issue has not arisen again. Equally, in order to confirm this diagnosis it has been shown that running the PDMS extruder independently in a clamp stand for similar time periods does not result in the same problem.

3.7 Functional Materials Development

Given the success achieved creating a multiple material component, work transferred to the deposition of functional materials. The preliminary investigations discussed here focus on two distinct areas: ferrites and electrical conductors.

3.7.1 Ferrites

Whilst some success has already been achieved 3D printing IMPC actuators, they author contends that the displacements achieved are insufficient for most electro-mechanical devices and rely on expensive and rare materials. In addition, if we were to study the devices used by society in day-to-day life the majority would be implemented either using electric motors or a solenoids. Whilst such devices require complex geometries, it can be said that 3D printing technologies lend themselves to producing such intricate components. For these reasons the author has elected to pursue the development of a ferrite material compatible with robocasting.

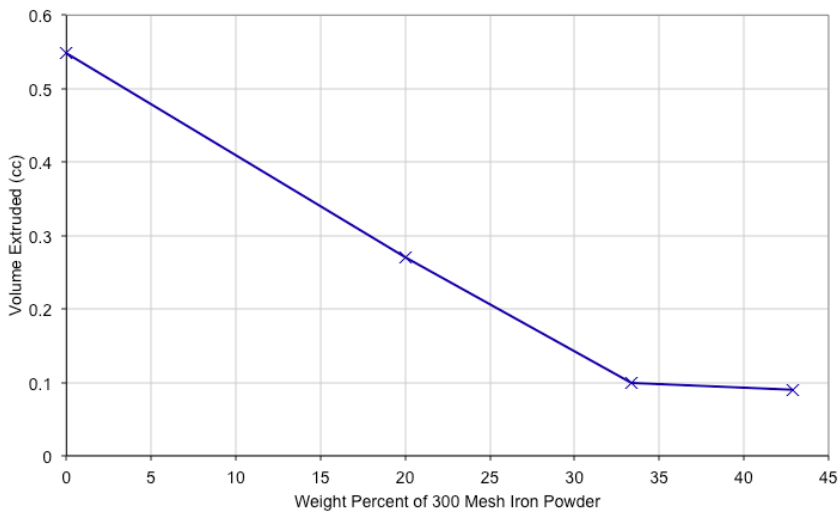


Figure 3.13: Graph showing the effects of iron quantity in the composite material on the extrusion rate. Tests are conducted using 300 mesh iron powder in a 10cc syringe loaded with 4cc of material at 1.6bar over a five minute period when utilising .

Given the experience already gained at this stage of research, it was decided to mix ferrite powders with the PDMS previously implemented to make a flexible magnetic material. If required the composition of the material could be adjusted to allow the extrusion characteristics as well as the magnetic properties to be controlled. Research thus far has focused on assessing the effect of material composition on extrusion characteristics for 300 mesh iron powder[3] and PDMS.

Figure 3.13 shows the results of the investigation conducted so far using a similar setup to that previously described. It can be seen that at low weight percent of iron powder, flow rates decrease linearly with increasing powder content. This has been attributed to the increase in viscosity associated with the addition of powder. The extrudate produced, being silicone based, allows for substantial deflections, estimated at 2-3cm for thin filaments, when in the presence of a 10mm dia x 3mm neodymium magnet as shown in Figure 3.14. Therefore these preliminary results are promising, and the measurements taken should allow calculation of the parameters needed to calculate the required deposition path.

[3]Purchased from Pyrotechnic Supplies

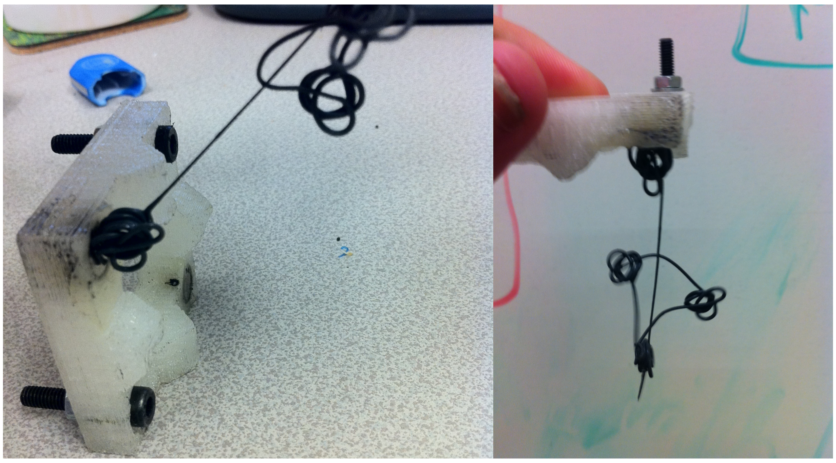


Figure 3.14: Flexible PDMS & Iron based ferrite composite. Note the ability for substantial deformations (left) and the support its own weight

3.7.2 Electrical Conductors

To summarise previous work undertaken, RCME techniques have shown promise. However the high surface tension of the materials employed lead to difficulty in controlling the deposition process. Therefore RCME results in large track widths of approximately 3mm being required for neat results. In addition, the low melting point of the materials employed ensured soldering was difficult. Alternatively, carbon graphite loaded adhesives (also known as wire glue) have been utilised with some success, but have high resistances. This means they are not suitable for high-current circuits.

It was proposed by the author that the paste-like characteristics of carbon black loaded adhesives are ideal for extrusion, and that potentially circuits could be post-processed to lower the resistance. If typical electronic circuits and components are studied, nearly all designs assume negligible track resistance. In addition, readily-available solders are typically specifically designed to adhere to copper. Therefore, the author contended that by electroplating the adhesive with copper, low resistances could be achieved whilst maintaining the desired extrusion characteristics and solderability.

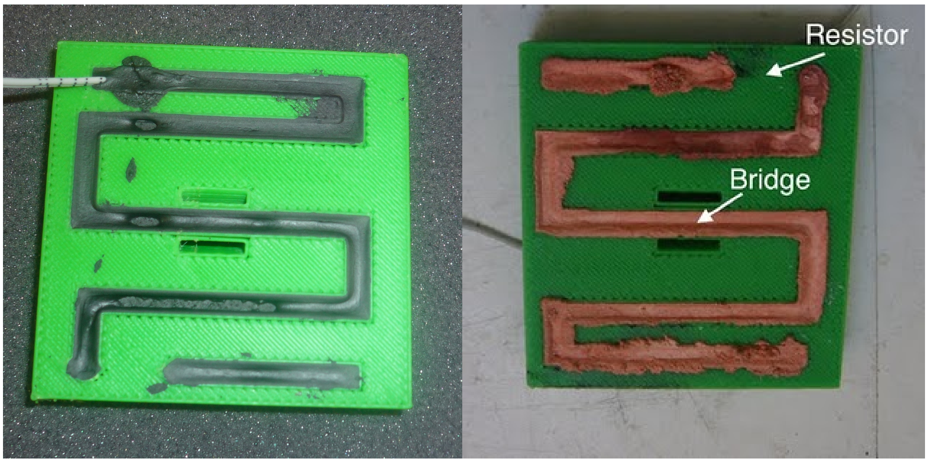


Figure 3.15: Example of a carbon black copper plating test piece, before (left) and after plating (right). The example shown was plated for 16 hours at 0.1A.

Utilising a saturated copper sulphate solution together with 2M sulphuric acid in a 40:1 ratio as defined by pre-existing literature, an attempt was made to plate a small amount of carbon wire glue. A simple channel of 3mm width was produced in a Stratasys rapid prototyper, and filled with commercially acquired graphite-loaded glue. The adhesive was subsequently connected to the anode of a constant-current power supply, and the cathode connected to a small copper pipe, and the entire system left in the copper sulphate solution. Figure 3.15 shows an example of the results achieved.

It was proposed that the flexibility of AM could be harnessed to give extra capability using the technique. By burying a section of the adhesive under thermoplastic, this section would be prevented from being plated and therefore maintain its original high resistance. Thus, the method offers the potential for both resistors and conductive track to be deposited utilising the same material all in one shot. On testing this theory, it was found that track would only be plated up to the buried section regardless of the current settings or the plating time. On reflection, this is the logical outcome. The current applied during electroplating is indicative of the electrons transferred in the process and hence the plating speed. Given the current is proportional to resistance, in low resistance sections of track the current, and therefore plating rate is high, whilst the opposite is also true. Therefore, low resistance sections of track are plated quicker, further lowering the resistance creating a self-reinforcing process.

In order to avoid this issue, its was proposed that a fugitive section of track, known as a bridge, may be produced to short circuit the resistor and to allow plating to continue. Upon completion of the plating process, this bridge was designed such that it may easily be broken away, removing the short circuit. This was trialled and worked as planned as shown in Figure 3.16. However, this technique requires that the end-user has access to each bridge, and thus the flexibility of the technique is slightly reduced.

The “resistor” shown was 10mm long and its resistance came to 2kΩ, whilst all of the copper plated sections had a resistance of 0Ω (or rather, it was so low as to be unmeasurable on the multimeter used). Further, given that the tracks are made of copper, components may be soldered to them easily. Therefore it can be concluded that the technique is capable of producing both functional resistors and useful low-resistance track.

It can also be seen that prior to plating significant shrinkage and cracking of the adhesive has occurred during curing, as previously demonstrated by Malone. However, plating repairs the tracks to a substantially more even surface.

Finally, an attempt was made to create the substrate using RepRap. It was found that standard settings resulted in the structure being porous to the carbon-loaded adhesive. This was therefore unsuccessful. Whilst work could easily be undertaken to remedy this issue, it exposes a further strength of the method. If the porosity of the substrate was actively controlled, the copper sulphate solution may seep into the structure in order to plate track within a fully-enclosed 3D structure. However, given the issue mentioned ensuring short sections of track are built where resistors are produced, work on this technique has been stopped until more time is available to follow up these interesting possibilities.

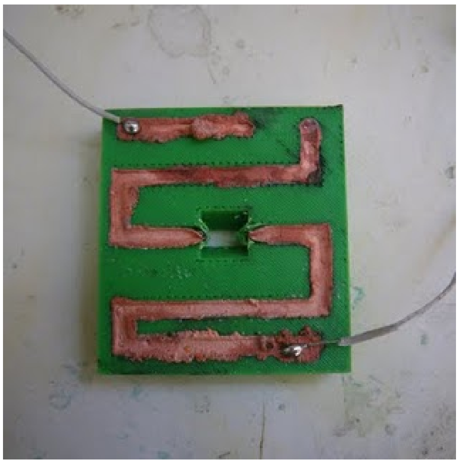


Figure 3.16: Copper plating test sample demonstrating a fugitive bridge.

Chapter 4

Conclusion

This report has defined the aim and goals required in order to manufacture complex electromechanical components using additive manufacturing technologies. An initial literature survey has been conducted to investigate prior art in the fields additive manufacturing, and examined within the context of the aims of this project

The research and mechanical development over the past year has been summarised. A suitable prototype has been developed to enable the deposition of multiple materials utilising the Robocasting and Fused Filament Fabrication processes. This architecture has been proved suitable to enable the manufacturing of multiple material components, and therefore preliminary experiments have been conducted towards the deposition of functional materials.

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